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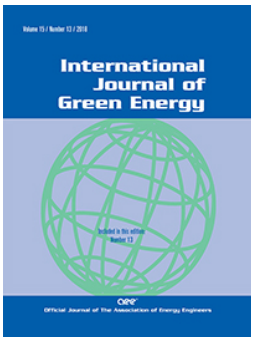

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Experimental investigation and comparison of energy consumption of electric and conventional vehicles due to the driving pattern

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ABSTRACT

In this paper, energy consumption of two light-duty vehicles, battery electric and conventional with an internal combustion engine, was investigated on the basis of chassis dynamometer test results. The sensitivity of energy consumption to various zero-dimensional characteristics of the driving pattern was discussed. The results demonstrated that under dynamic driving conditions, the electric vehicle used on average 64% less energy than the conventional one, even with battery charging efficiency taken into account. Among selected zero-dimensional characteristics, the average velocity and the average absolute value of the product of velocity and acceleration proved to be the best characteristics to describe the energy consumption of vehicles.

KEYWORDS

Conventional vehicles; driving pattern; driving test cycles; electric vehicles; energy consumption

1. Introduction

In the twenty-first century, the automobile market confronts great challenges as a variety of environmental problems, relevant to motor vehicles, have emerged. Those include, in particular, air pollution and its impact on health (Dąbrowiecki et al. 2015; Jakubiak-Lasocka et al. 2015), global warming (Sun, Su., and Shao 2016), and the depletion of natural resources which leads to the rise of international oil prices (Fiorito and van Den Bergh 2016). Transforming challenges into opportunities, the automotive industry has made efforts to develop eco-friendly vehicles, not only by increasing the efficiency and emission control of the conventional vehicles equipped with internal combustion engines (ICEVs) (Samoilenko and Cho 2013) but also by introducing for sale vehicles that use electric power, i.e., battery electric vehicles (BEVs) and hybrid electric vehicles (HEV) (Fornahl and Hülsmann 2016).

Electrification of the automotive powertrains is often believed to be the viable solution for achieving high energy efficiency of vehicles (Wang, Zhang, and Ouyang 2015). However, further development of BEVs is limited by the shortcomings of available battery designs, which contribute to the short driving range, short battery life, and long charging time (Kobayashi, Plotkin, and Ribeiro 2009; Sweeting, Hutchinson, and Savage 2011). Given the range of limitations of BEVs, driving pattern becomes a crucial issue that determines vehicle energy consumption, environmental impacts, and economic costs. Therefore, driving pattern and its characteristics are being studied, providing data necessary for the optimization of vehicle design, its control, and even battery charging infrastructure construction (Al-Alawi and Bradley 2013; Chmielewski et al. 2016).

It is widely known that the way the car is driven, regardless of its powertrain type, containing electric motor engine or ICEV, affects energy consumption. Neubauer, Brooker, and Wood (2012) have developed a model for a total cost of ownership of BEVs, employing real-world driving data, and found that the energy consumption is highly sensitive to vehicle-specific driving patterns. Wang, Zhang, and Ouyang (2015) assessed the energy consumption reduction associated with BEVs compared to ICEVs in real-world driving conditions in Beijing. The results indicated that BEVs yield more energy consumption reduction benefits in severe driving conditions and short driving ranges. Karabasoglu and Michalek (2013) compared the potential of BEVs, HEVs, and ICEVs to reduce lifetime cost, which depends to some extent on energy consumption, and life-cycle greenhouse gas emissions under various simulated driving conditions. They found that because driving conditions significantly affect the economic and environmental benefits of BEVs and HEVs, those vehicles perform better than ICEV only while tested in particular drive cycles. Jeong et al. (2016) stressed that there are large differences between the drive system and driving characteristics of BEV and that of ICEV. In their study, the special urban driving cycle for BEVs was developed using driving data obtained through actual driving experiments and statistical analysis. Neubauer and Wood (2013) focused on driver aggression to quantify its effect on BEV, HEV, and ICEV energy efficiency. Numerical simulations and empirical data revealed that the ideal driving behavior, bringing high energy efficiency, varies

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with respect to powertrain type. Besides, BEVs and HEVs show higher efficiency than ICEVs in low average velocity traffic and frequent stop-and-go conditions.

The aim of this paper was to analyze and compare the influence of different parameters characterizing driving pattern on energy consumption of BEV and conventional vehicle equipped with an ICEV. To exclude the effect of vehicle design parameters and to maximize the objectivity of the comparison, two variants of the same light-duty vehicle model, differing only by powertrain type, were chosen for experimental work. The investigation involved carrying out a series of standard (type-approval) and special driving test cycles on a chassis dynamometer followed by a discussion on the sensitivity of obtained results to several driving pattern characteristics.

2. Driving pattern characteristics

The concept of driving pattern, commonly referred to as a driving style, is generally defined as the variation of vehicle velocity with time but can be extended to other factors, including gear changing, driving distance, etc. (Ericsson 2001; Neubauer, Brooker, and Wood 2012). Since there is no simple solution for quantifying driving patterns, a lot of different characteristics have been developed to serve this purpose (Ericsson 2001). One common approach is to use velocity- and acceleration-related parameters.

The research works on driving pattern of vehicles date back to early 1970s due to their influence on pollutant emissions and fuel consumption. Kuhler and Karstens (1978), for example, introduced a group of 10 zero-dimensional characteristics of driving pattern which are still frequently used: average velocity, average driving velocity (excluding stops), average acceleration, average deceleration, average driving time within one driving period (from start to stop), average number of acceleration–deceleration changes (and vice versa) within one driving period, share of standing time, share of acceleration time, share of time at constant speed, and share of deceleration time. André (1996) provided a review of the state-of-the-art research in relation to commonly used driving pattern characteristics. Apart from those mentioned previously, he selected the following: standard deviation of velocity and acceleration, positive kinetic energy, number of stops per distance, and relative and joint distribution of velocity, acceleration, and deceleration. Fomunung et al. (1999) in his model for NO_x emission used characteristics representing surrogates for power and torque, i.e., product of the velocity and acceleration as well as the product of the squared velocity and acceleration. Ericsson (2001) calculated values of 62 driving pattern characteristics, including engine speed and gear changing, for data collected in real traffic. These were then reduced to 16 independent driving pattern parameters, 9 of which were found to have significant environmental effects – 4 associated with velocity and acceleration, 3 describing gear changing, and 2 related to the effect of certain speed intervals. Up to now, most of the existing standard and special driving cycles were compared and contrasted in terms of their zero-dimensional characteristics; e.g., Barlow et al. (2009) calculated 42 most relevant characteristics for 256 driving cycles and presented them in the Reference Book.

On the basis of literature review, six zero-dimensional characteristics of the driving pattern were chosen for consideration in this study:

- Average velocity [km/h],
- Share of time when the vehicle is stopped (velocity equals 0) [%],
- Average positive acceleration [m/s^2],
- Average negative acceleration [m/s^2],
- Relative positive acceleration [m/s^2],
- Average absolute value of the product of velocity and acceleration [m^2/s^3].

The above characteristics were found to be particularly important for experimental investigation and modeling of energy consumption of vehicles (Ericsson 2001, 2005). The average value of the positive acceleration determines the demand for maximum engine torque. Relative positive acceleration is calculated as the integral of velocity multiplied with positive acceleration and the time interval when the acceleration is positive and divided by the total distance of the drive. Relative positive acceleration value is large for a driving pattern that includes a lot of high power-demand accelerations and is found to increase fuel consumption. The average value of absolute value of the product of velocity and acceleration can be interpreted as a measure of engine power output per unit mass of the vehicle.

3. Tested vehicles

Two Renault Kangoo utility vans were used for the tests (Figure 1): model Z.E., equipped with a synchronous electric motor, and model 1.5 dCi, with an internal combustion compression–ignition engine. The Kangoo Z.E. has the same dimensions as the internal combustion version of the model and shares most of its parts. Detailed information on the tested vehicles is shown in Table 1.

4. Apparatus

Driving test cycles were performed on Schenck-Komeg EMDY 48 chassis dynamometer. Pollutant concentration from ICEV was measured with the use of Horiba Mexa 7200 system consisting of exhaust gas analyzers: AIA-721A (for carbon monoxide), AIA-722 (for carbon dioxide), MPA-720 (for oxygen), CLA-755A (for nitrogen oxides), and FIA-725A (for hydrocarbons). Energy consumption of an electric vehicle was measured with the use of electricity meter Pafal PRL T3195 type A52.

5. Methods

Experimental work was carried out on a chassis dynamometer with the use of the following driving test cycles (Figure 2):

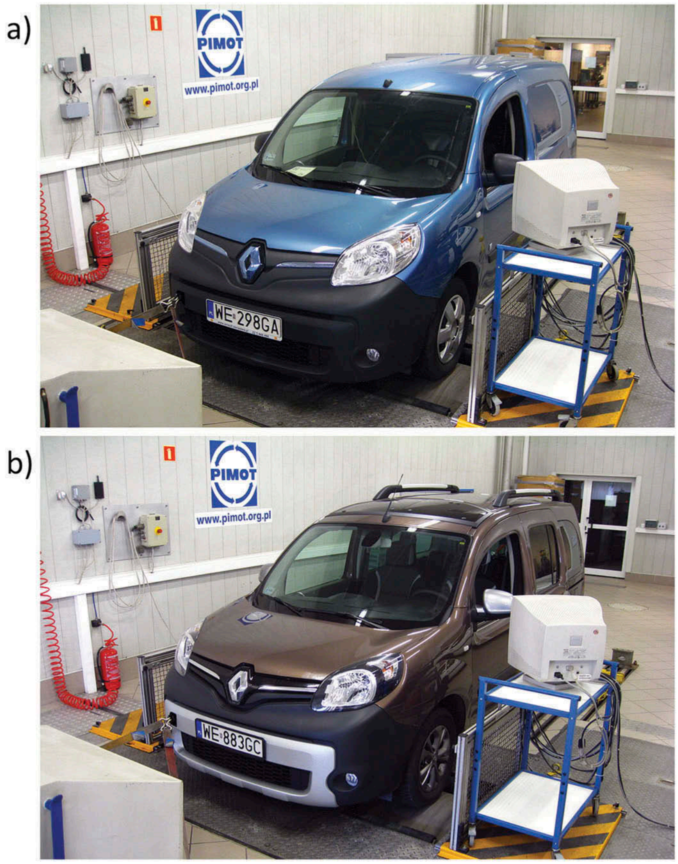

Figure 1. Vehicles used for tests on chassis dynamometer: (a) Renault Kangoo Express Z.E. (BEV) and (b) Renault Kangoo 1.5 dCi (ICEV).

- Type approval: UDC (Urban Driving Cycle), EUDC (Extra Urban Driving Cycle), NEDC (New European Driving Cycle, consisting of UDC and EUDC), and FTP-72 (Federal Test Procedure),
- Special: Stop and Go, simulating driving in street congestion, and PIMOT UT 1, simulating driving in urban areas without street congestion, developed in the Automotive Industry Institute in Warsaw, Poland (Chłopek et al. 2015).

Average distance energy consumption for the BEV was determined by performing a series of driving test cycles of one type and then measuring energy consumption during charging fully the battery pack. The number of cycles in each series was as follows[1]: 8 UDC, 10 EUDC, 6 FTP-72, 5 Stop and Go, 8 PIMOT UT1. Battery charging was carried out in accordance with "normal overnight charge procedure," set out in UNECE Regulation No 101, which takes into account energy losses during charging. Manufacturer's standard 220–230 V charger was used. Ambient temperature during charging was maintained between 20°C and 25°C.

In case of ICEV, average distance-specific energy consumption in each type of test cycle was derived from average operational fuel consumption. The latter quantity was calculated from the results of measurements conducted on a chassis dynamometer, i.e., distance-specific emission of hydrocarbons, carbon monoxide, and carbon dioxide, using balance of carbon mass method defined in UNECE Regulation No 101:

$$Q_{ICEV} = \frac{0.1155}{\rho}\left(0.866 b_{HC} + 0.429 b_{CO} + 0.273 b_{CO_2}\right)\left[dm^3/100km\right]$$

where

ρ – fuel density (0.83 g/cm^3),

b_{HC} – distance-specific emission of hydrocarbons [g/km],

b_{CO} – distance-specific emission of carbon oxide [g/km],

b_{CO2} – distance-specific emission of carbon dioxide [g/km].

Each type of driving test cycle was performed three times with the combustion engine warmed up to normal operating temperature. Additionally, UDC and NEDC test cycles were repeated also with cold engine start. Calorific value of diesel oil was assumed to be 43 MJ/kg.

Ambient conditions were constantly monitored during all measurements made on chassis dynamometer. The air temperature was maintained at 23–26°C with the average of 25°C, the air pressure ranged 996–1008 hPa with the average of 1001 hPa, and the air relative humidity ranged 15–23% with the average of 18%. The exhaust gas analyzer system used automatically compensated the potential impact of the changes of ambient conditions.

6. Results and discussion

Average distance-specific energy consumption for both vehicles in various driving test cycles is shown in Figure 3. It includes vehicle driving and battery charging but does not cover the efficiency of fuel production and electricity generation as well as their transportation and distribution.

It is clearly visible that BEV uses less energy than ICEV, regardless of driving cycle employed. The relative difference between vehicles (relative to ICEV) equals 50–78%, depending on the driving cycle, with the average of 64% (62% without cold start tests). This is primarily due to the higher efficiency

Table 1. Overview of the tested vehicles.

	BEV	ICEV
Make	Renault	Renault
Model	Kangoo Express Z.E.	Kangoo 1.5 dCi
Year of manufacture	2013	2013
Curb weight [kg]	1485	1507
Engine type	Synchronous electric motor with wound rotor	CI internal combustion engine, supercharged, four-cylinder, common rail fuel supply system
Engine displacement [dm^3]	–	1.461
Maximum power [kW]	44	81
Maximum torque [N· m]	226	240
Maximum speed [km/h]	130 (electronically limited)	170
Battery pack	lithium-ion, 22 kWh	–

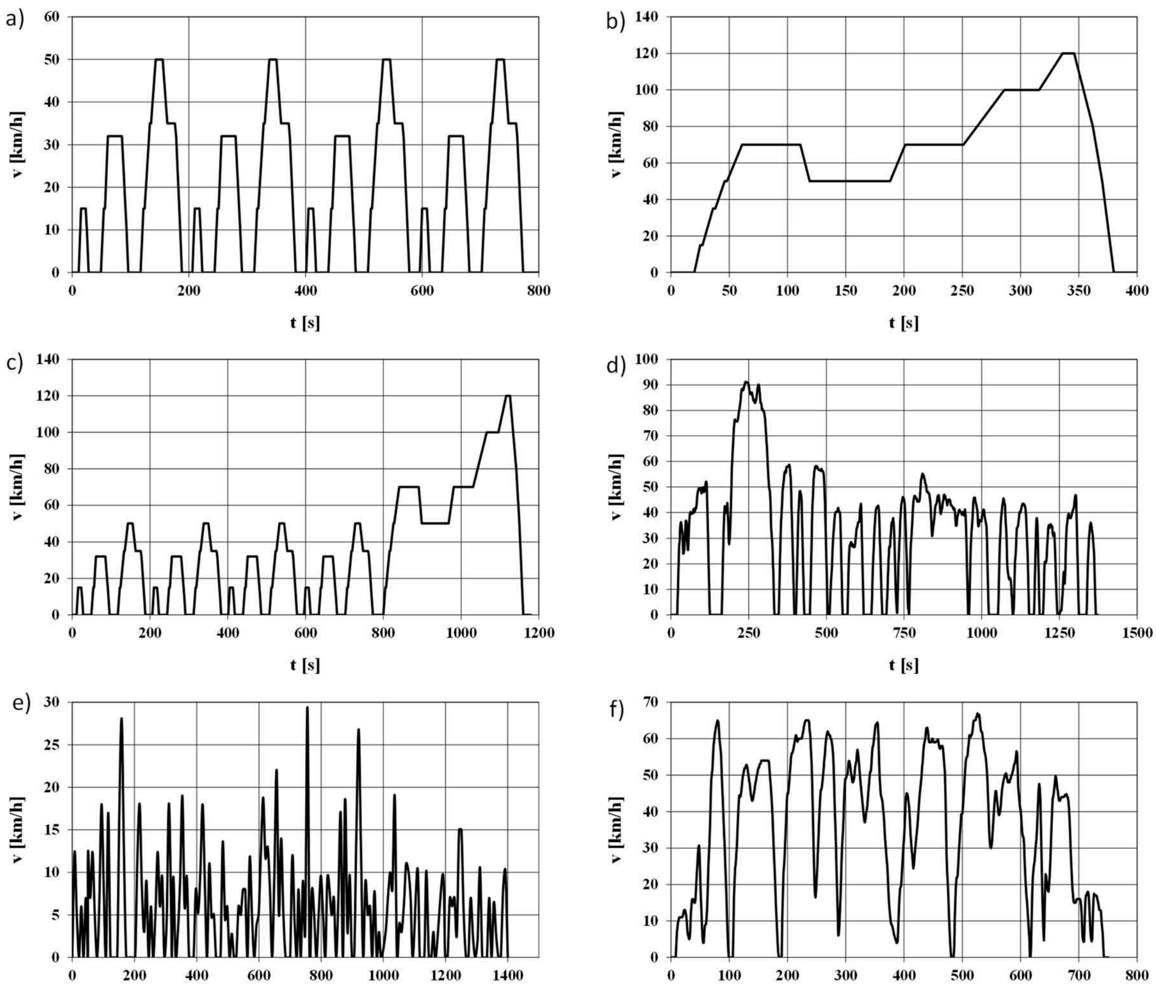

Figure 2. Driving test cycles included in the study: (a) UDC, (b) EUDC, (c) NEDC, (d) FTP-72, (e) Stop and Go, and (f) PIMOT UT1.

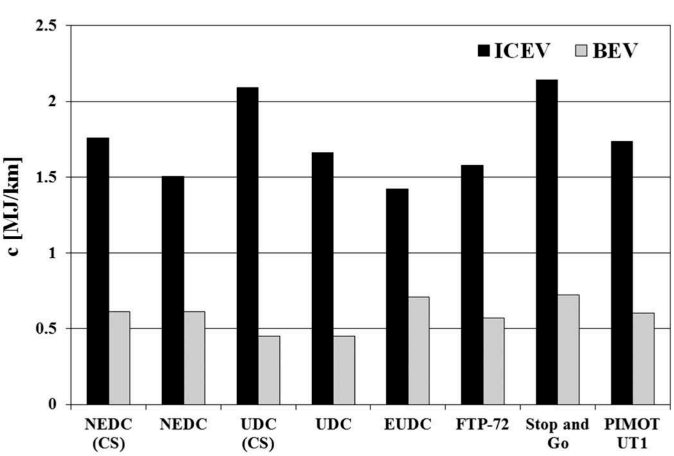

Figure 3. Average distance-specific energy consumption (c) in driving test cycles (CS – cold start).

of electric motors than combustion engines (Sweeting, Hutchinson, and Savage 2011). It should be emphasized that most of the driving cycles used in this study represent traffic conditions typical for urban areas, with a large share of braking. Such conditions favor BEV, which is equipped with a braking energy recovery system. This is further confirmed by the fact that the smallest relative difference between the energy consumption for both cars is in EUDC, the only one which simulates extra-urban traffic conditions.

In addition, for UDC and NEDC, the effect of a cold start of the combustion engine can be investigated (Arumugam et al., 2015). It increases its energy consumption by 17% and 26%, respectively. Such an effect does not apply to an electric motor.

To investigate the influence of various driving patterns on energy consumption, the results of dynamometer tests were plotted against different characteristics: average velocity (Figure 4), share of time when vehicle is stopped (Figure 5), positive acceleration (Figure 6), negative acceleration (Figure 7), relative positive acceleration (Figure 8), and average absolute value of product of velocity and acceleration (Figure 9). Only results of tests with the warm start of the combustion engine are included. The sets of points are approximated by polynomial functions of a second degree.

Analysis of all considered dependencies indicates that energy consumption is sensitive to the vehicle driving pattern, described here by zero-dimensional characteristics. Among them, the average velocity and the average absolute value of the product of velocity and acceleration

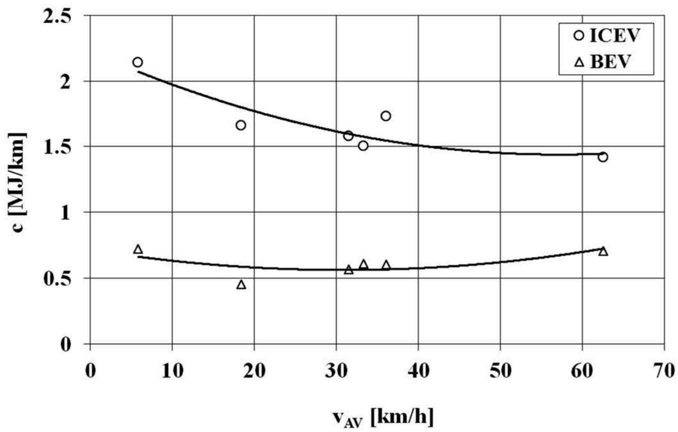

Figure 4. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the average velocity (v_{AV}) in driving test cycles.

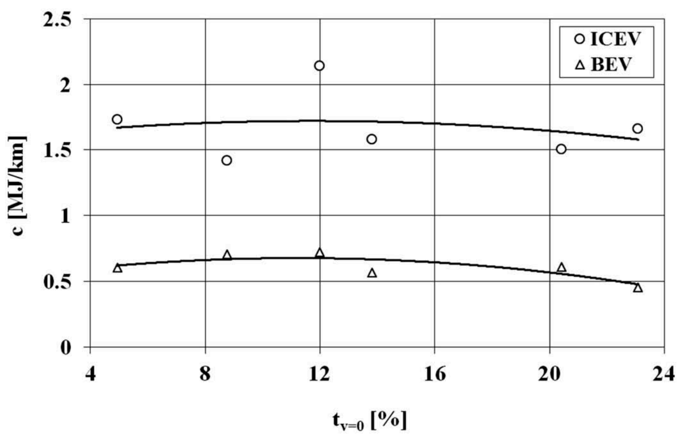

Figure 5. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the share of time when the vehicle is stopped ($t_{v=0}$) in driving test cycles.

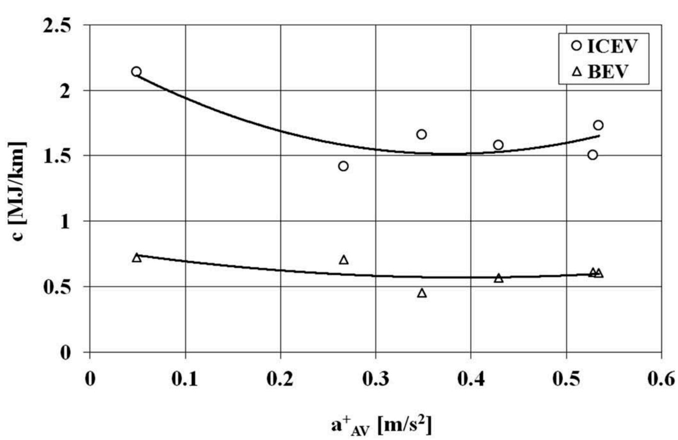

Figure 6. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the average positive acceleration (a^{+}_{AV}) in driving test cycles.

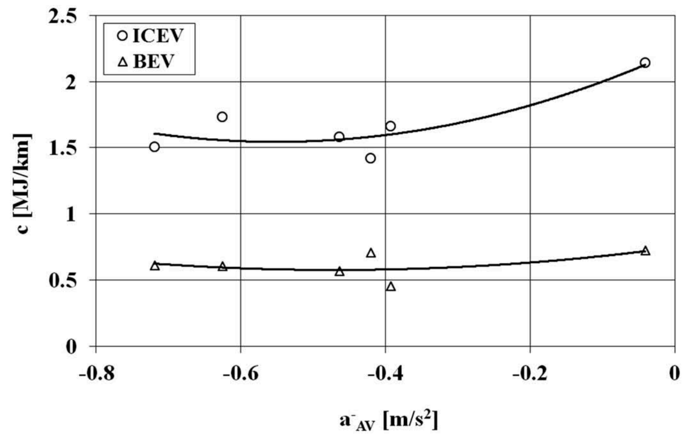

Figure 7. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the average negative acceleration (a^{-}_{AV}) in driving test cycles.

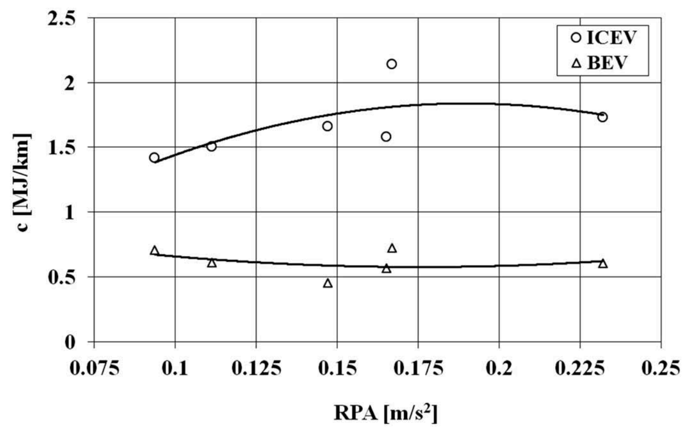

Figure 8. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the relative positive acceleration (RPA) in driving test cycles.

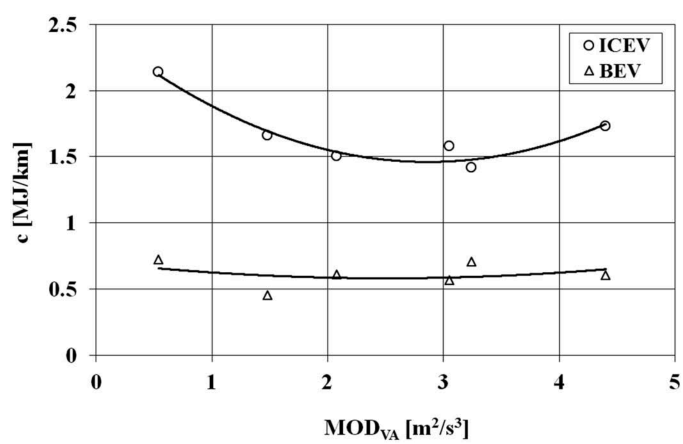

Figure 9. Dependency of the distance-specific energy consumption (c) of ICEV and BEV on the average absolute value of the product of velocity and acceleration (MOD_{VA}) in driving test cycles.

demonstrate the greatest uniformity of distribution of points, which correspond to energy consumption in each driving cycle. They are followed by the characteristics associated with average acceleration, positive as well as negative. On the other hand, a greater spread of points was obtained for relative positive acceleration and share of time when the vehicle is stopped, in particular in the moderate values of those characteristics. This observation is consistent for both BEV and ICEV.

As expected, energy consumption of BEV is always lower than of ICEV, regardless of the characteristic of driving pattern. In general, almost all approximations of characteristics of one type have a similar shape, including the occurrence of extrema, for both vehicles. The exception is relative positive acceleration, in which extremes for BEV and ICEV are reversed. An important observation based on the experimental results is that the curvature of all the approximations for BEV is very small, which may indicate that energy consumption of this type of powertrain is not particularly sensitive to the driving pattern. This is quite different from approximations of ICEV energy consumption, for which curvature is much larger. For example, a closer look at the plots of average velocity reveals that in the conditions of low average vehicle velocity, which correspond to severe traffic conditions, energy consumption of combustion engine reaches its highest values, while energy consumption of electric motor increases only slightly.

Interpreting the results of this study, it should be taken into account that most of the chosen driving cycles simulate urban or semi-urban conditions, which consist of a large proportion of acceleration, deceleration, and stop phases at low or medium velocity. Further research should include more driving cycles representing other traffic conditions, with special emphasis on driving at high velocity, typical for highways.

Another issue is the determination of other characteristics of driving pattern and their use for investigation of differences between the energy consumption of vehicles with both types of the propulsion system. In addition, there is also the possibility of determining multidimensional characteristics of energy consumption depending on several parameters. Some parameters determining energy consumption are probably correlated in real traffic, making the results difficult to interpret correctly.

7. Conclusions

The energy consumption of vehicles, irrespective of their propulsion system, with an electric motor or a combustion engine, is influenced not only by their construction features but also by operating conditions, including the driving pattern. This study focused on investigation and comparison of energy consumption of BEV and ICEV, having the similar construction of the chassis and body, driven on a dynamometer in various driving test cycles. The results were discussed by identifying trends in energy consumption with respect to zero-dimensional characteristics of the velocity of the vehicles.

From the outcome of this investigation, the following major conclusions can be drawn:

(1) Under dynamic driving conditions, ICEVs use more energy than BEVs, even with the charging efficiency taken into account. For driving cycles considered in this study, the relative difference between two vehicles equals 50–78% with the average of 64%. This is determined mainly by higher efficiency of electric motor engine than ICEV and the ability of BEV to recover energy from braking.

(2) The results obtained demonstrate that energy consumption of ICEV is much more sensitive to driving pattern compared to BEV.

(3) Among selected zero-dimensional characteristics, average velocity and the average absolute value of the product of velocity and acceleration proved to be the best to predict energy consumption of vehicles. Other important parameters are average positive and negative acceleration.

(4) The conducted experimental investigation and obtained results confirmed the necessity of developing and application of zero-dimensional characteristics for the assessment of energy consumption of vehicles in different traffic conditions.

Note

1. Total number of driving cycles performed with BEV varied because of the duration of each cycle.

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