Article citation info:
PIELECHA I, CIEŚLIK W, SZAŁEK A. Operation of electric hybrid drive systems in varied driving conditions. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (1): 16–23, http://dx.doi.org/10.17531/ein.2018.1.3.

Ireneusz PIELECHA
Wojciech CIEŚLIK
Andrzej SZAŁEK

OPERATION OF ELECTRIC HYBRID DRIVE SYSTEMS IN VARIED DRIVING CONDITIONS

EKSPLOATACJA ELEKTRYCZNYCH UKŁADÓW NAPĘDOWYCH POJAZDÓW HYBRYDOWYCH W ZRÓŻNICOWANYCH WARUNKACH RUCHU*

Hybrid vehicles allow an increase in the powertrain efficiency thanks to their design. One such factor is the use of increased voltage supplying electric motors to the voltage supplying the high voltage battery. The battery voltage is increased several times in the inverter (boost) system to increase the final electric power supplied to the electric motor. The article presents the possibilities of using such a voltage boost in urban and non-urban driving conditions. The tests were performed on the latest generations of parallel hybrid drive systems in Lexus NX 300h and Toyota RAV4 hybrid vehicles. It has been shown that the boost system is used in about 30–40% of the urban drive distance (up to 20% of the driving time). The power supply voltage boost of the electric motors of both vehicles is used throughout the entire engine speed range of these machines at high torque values. Research has shown that the maximum voltage gain – approximately three times (up to 650 V) – is within the maximum torque range of the electric motors and allows for doubling the torque generated by the drive.

***Keywords**: electric motor, current generator, hybrid drive, voltage boost, energy flow, high voltage battery.*

Pojazdy z napędem hybrydowym dzięki swojej konstrukcji, pozwalają na zwiększenie sprawności układu napędowego. Jednym z takich czynników jest stosowanie zwiększonego napięcia zasilającego silniki elektryczne w stosunku do napięcia zasilającego akumulator wysokonapięciowy. Napięcie akumulatora zostaje zwiększone kilkukrotnie w układzie inwertera (boost) w celu zwiększenia końcowej mocy elektrycznej doprowadzonej do silnika elektrycznego. W artykule przedstawiono możliwości wykorzystania takiego wzmocnienia napięcia w warunkach jazdy miejskiej i pozamiejskiej. W badaniach wykorzystano najnowsze generacje układów napędu hybrydowego równoległego w pojazdach Lexus NX 300h oraz Toyota RAV4 hybrid. Wykazano, że układ wzmocnienia napięcia w warunkach miejskich wykorzystany jest w około 30–40% dystansu (do 20% czasu jazdy). Wzmocnienie napięcia zasilającego maszyny elektryczne obu pojazdów wykorzystane jest w całym zakresie prędkości obrotowej tych maszyn przy dużych wartościach momentu obrotowego. Badania wykazały, że maksymalne wzmocnienie napięcia – około trzykrotne (do wartości 650 V) – występuje w zakresie maksymalnego momentu obrotowego silników elektrycznych i pozwala na ponad 2-krotne zwiększenie generowanego momentu obrotowego układu napędowego.

***Słowa kluczowe**: silnik elektryczny, generator prądu, napęd hybrydowy, wzmocnienie napięcia, przepływ energii, akumulator wysokonapięciowy.*

1. Introduction

The variety of hybrid drives available from most passenger vehicles manufacturers means that the interest in the energy flow in such vehicles is very high. Vehicle hybrid drives have been dominated by parallel drives with independent internal combustion engine or electric motor propulsion. Parallel systems with the electric motor supporting the internal combustion engine – despite their simpler construction – are much less common. This is due to the less universal nature of such a hybrid drive solution in everyday urban and non-urban traffic [5].

Tests of vehicles powered with alternative fuels or with alternative propulsion systems are carried out with respect to their respective harmful components emissions [6, 8, 9]. Increasingly more often, these studies refer to conditions of energy flow in hybrid [12] or electrical systems [3]. The theoretical and road analysis of the increased energy recovery potential through the use of different gearing reduction strategies is described in [4]. There are currently many models of hybrid drive systems [1, 2, 11, 13], but road tests of such systems are the basis for the verification of simulation test results.

Current hybrid drive solutions, despite the use of batteries with rated voltages between 200 V and 250 V, allow the electric motors to operate on up to 650 volts. This input voltage gain allows for a 2.5 to 3 times increase in the nominal voltage. Voltage converters are described in [7, 10], among others.

Previous studies have not dealt with the issue of the effect of changes in the electric motor supply voltage to its operating conditions. Taking this into account, the authors have divided the voltage boost value into several compartments:

a) $U < 300$ V,
b) $300 \text{ V} \leq U < 400$ V,
c) $400 \text{ V} \leq U < 500$ V,
d) $500 \text{ V} \leq U < 600$ V,
e) $U \geq 600$ V.

2. Motivation

Varied solutions used in passenger vehicles with hybrid drive systems make the comparison of their mechanical or electrical characteristics ineffective. The use of identical hybrid drive systems allows

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** for increased comparability, especially when mounted on two similar vehicles. The mechanical and electrical similarities of powertrain systems do not allow for the unambiguous affirmation of the similarity of their characteristics in terms of differentiated vehicle driving conditions. Thus, the motivation for the study was to analyze the driving characteristics of vehicles with hybrid drive systems. In addition, considering the increase in the supply voltage, the use of this voltage increase and its effect on the flow of energy in the hybrid drive systems of vehicles has been analyzed.

3. Methodology

The purpose of the research was to analyze the energy flow in vehicles equipped with the same hybrid powertrain system, taking the following aspects into account:

1. Analysis of electric vehicles working conditions during driving and regenerative braking.
2. Determining the conditions for using the increased voltage supply value for the electric motors.
3. Determining the flow of electric power in a hybrid vehicle including consumption and energy recovery in different driving conditions.

Analysis of these specific objectives was conducted using vehicles with a full hybrid (parallel) drive system. These vehicles also used an additional rear axle drive system with an electric motor. The only difference between the test vehicles was their curb mass (Table 1).

The research objectives, in addition to the research objects in the form of two hybrid vehicles, required the use of an instrument that would allow making measurements of the main electric parameters of their drive systems. Acquisition of the measured data at 16–38 Hz has been made, which allows for accurate estimation of the changes in the drive systems operation. The study was conducted using a dedicated TechStream diagnostic system for acquisition of measurement data from Toyota and Lexus vehicles (Figure 1).

Table 1. Technical parameters of the test vehicles

Parameter	Unit	Lexus NX 300h	Toyota RAV4 hybrid
Combustion engine			
Displacement	dm^3	2.494	←
Torque	Nm at rpm	206 at 4400–4800	←
Power	kW at rpm	114 at 5700	←
Electric drive system – front			
Torque	Nm at rpm	270 at 0–1800	←
Power	kW at rpm	105 at 4500	←
Electric drive system – back			
Torque	Nm	139	←
Power	kW	50	←
Electric energy storage system			
Battery	–	NiMH	←
Capacity	kW·h	1.59	←
Battery voltage	V	244.8	←
Maximum inverter voltage	V	650	←
Vehicle			
Curb weight	kg	1860	1735

a)
b)


Fig. 1. Vehicle test conditions using on-board diagnostic system reader designed for analysis of vehicles with hybrid drive systems

4. Research conditions

Analyzes of the vehicle propulsion systems were made using road tests in urban and non-urban areas in and around Warsaw. Using the technique of driving one after another (so-called following the leader) – Figure 2, it was found that both drives have similar parameters. The travel distance was 14.8 km (about 2450 s) in urban driving condi-

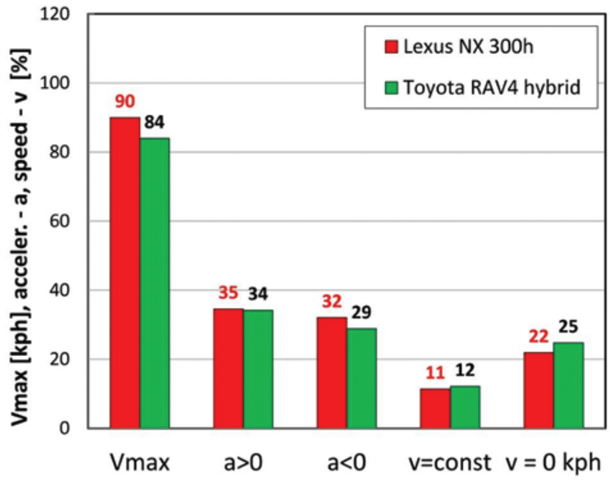
a)


Fig. 2. Tested vehicles speed comparison: a) in urban driving conditions

b)

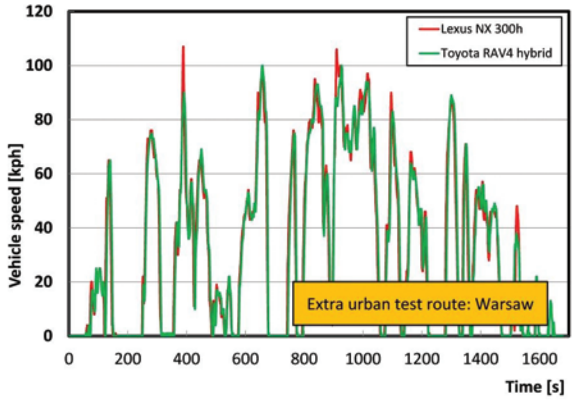


Fig. 2. Tested vehicles speed comparison: b) in non-urban driving conditions

a)

b)

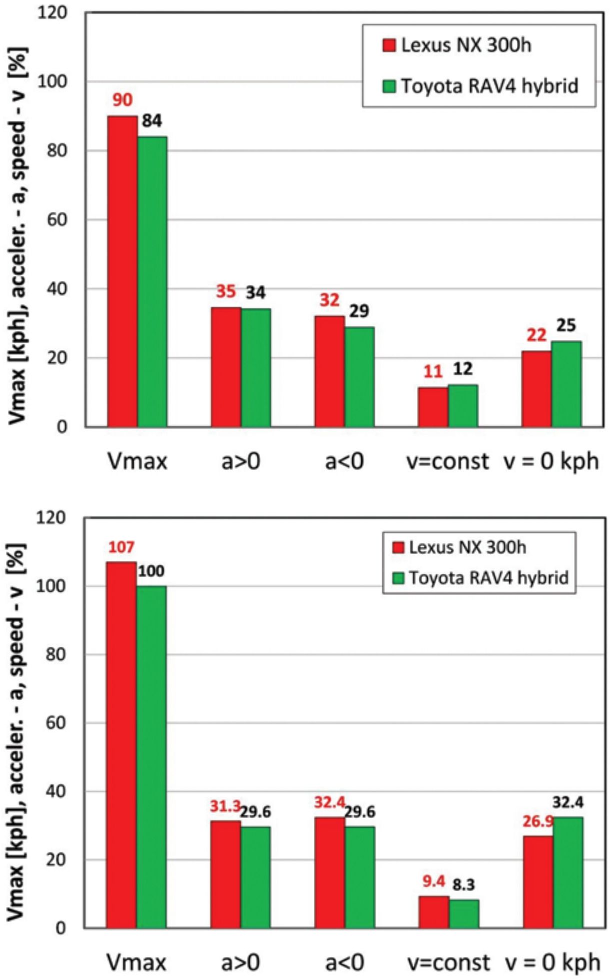


Fig. 3. Characteristic measured values of the test drives: a) in urban driving conditions, b) in non-urban driving conditions

tions and 14.6 km (about 1770 s) in non-urban driving conditions. In the first one the average speed was 24 km/h, while for the second case the speed was 33 km/h.

The similarity of the drives was further confirmed in the analysis of the maximum speed values as well as the time shares of accelerating and driving at constant speed. In urban traffic the maximum speed difference was 7% (Figure 3a). The same difference value was obtained in non-urban traffic (Figure 3b). Relative acceleration time in urban traffic was about 35%, while in non-urban traffic – about 30%. There was about a 5% difference. Relative braking time was about 30% in all test drives. Driving time at a steady speed was short and reached about 10% – slightly longer in urban driving. The drive time share of the vehicle being stationary was 22–25% in urban traffic, and 27–32% in non-urban traffic.

The analysis of these measured parameters allows determining the similarity of the two drives. This is a prerequisite for further analysis and the comparison of the operating conditions of two hybrid drives in urban and non-urban driving conditions. This analysis was carried out in the next chapter.

5. Operation of electric motors at variable voltage conditions

5.1. Comparison of the electric motors operating conditions during vehicle operation

The hybrid vehicles operation analysis was conducted mainly in relation to the electric systems of the vehicle drive. The analysis of the electric motors operation was carried out in the aspect of motor voltage supply intervals. According to the above-mentioned data, higher supply voltage values should be used at high torque values. An analysis of the electric motors performance characteristics of tested vehicles indicates the use of high voltages in the high torque range at medium engine speed (Figure 4 above 600 V). As the engine speed increases, the value of its supply voltage increases. Note that in non-urban driving conditions (higher driving speeds), a wider field of operating point values is used with higher voltages. In urban driving conditions (Figure 4a and 4b), the high density of operating points is visible for tor-

a)

b)

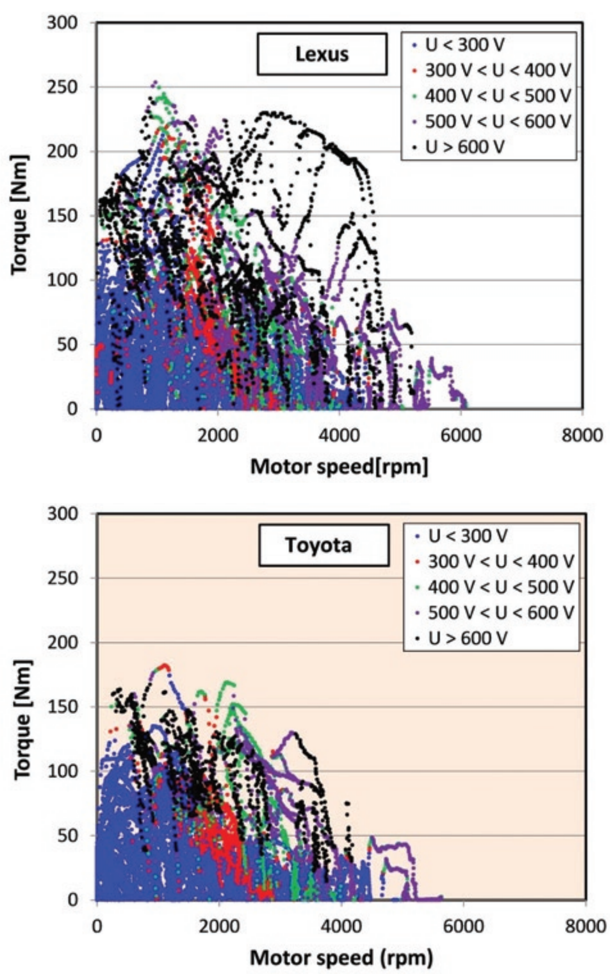


Fig. 4. Electric motors characteristics of the tested vehicles: a–b) in urban driving conditions relative to the supply voltage

c)

d)

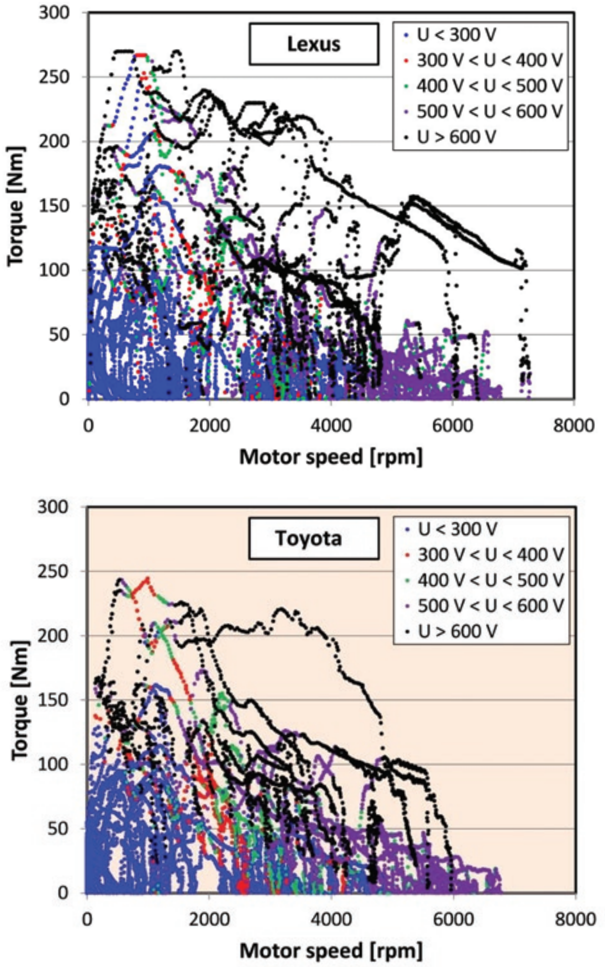


Fig. 4. Electric motors characteristics of the tested vehicles: c–d) in non-urban driving conditions relative to the supply voltage

ques up to 150 Nm and engine speed up to 6000 rpm. Higher values of maximum torque were observed when driving a Lexus car than for the Toyota vehicle. The analysis of this speed characteristic of the electric motor shows that at the given speed it is possible to supply the motor with different voltage values. This voltage increases proportionally to the required torque value. Increasing the supply voltage increases the electric motor power.

The characteristics of the power system means that the vehicle driving speed is proportional to the speed of the motor. It follows that with the driving speed increase in non-urban areas the engine speeds increase as well (Figure 4c and 4d). In non-urban driving conditions the differences in the areas used for the electric motors characteristics show smaller variations than in urban driving. The high torque values in the mean electric motor speed range values lead to the maximum electric motor output power in this range of motor speed. These maximum power values are generated at high voltages. Otherwise, according to the equation Ne = U × I, the powers would be limited (at the same current and a smaller voltage value).

5.2. Electric motors operating conditions comparison during regenerative braking

Recovering energy during braking allows observing the typical conditions of electric voltage change that lead to changes in the energy stored in the high-voltage battery.

The previous section has shown that the maximum values of the electric motor supply voltage occur at their maximum power. The conditions of voltage change during energy recovery are different (Figure 5). During braking, the voltage change from the current gen-

a)

b)

c)

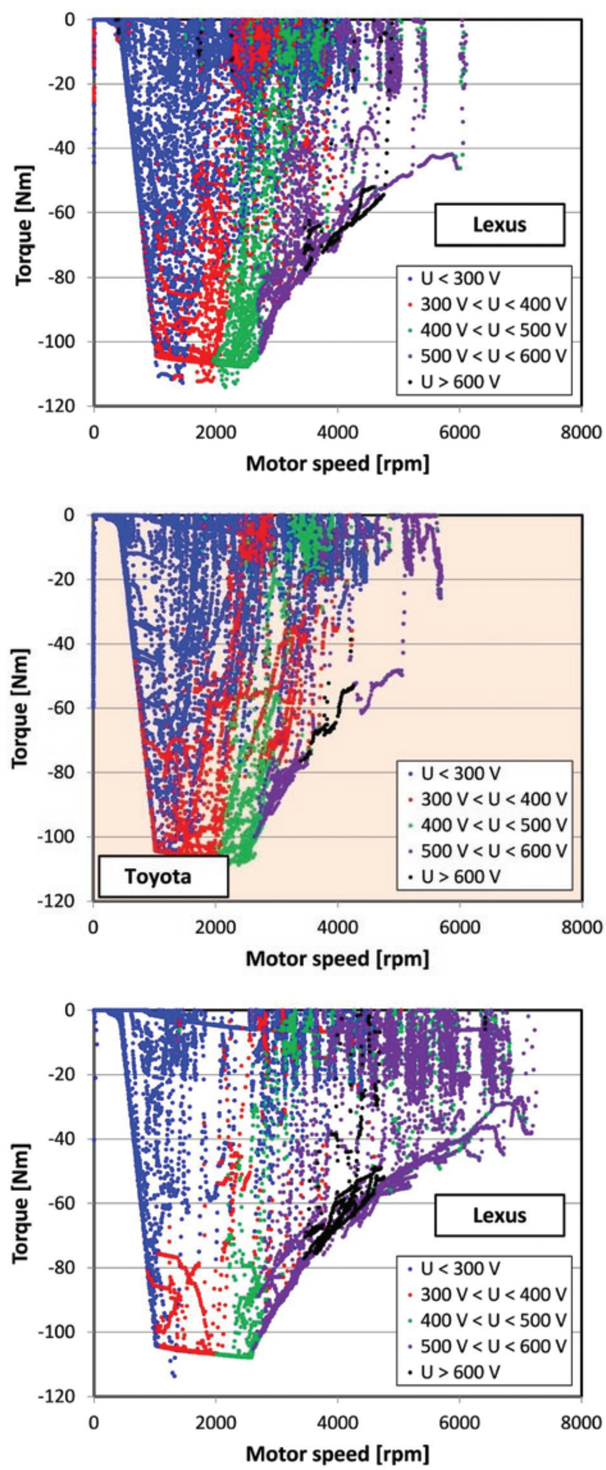


Fig. 5. Electric motor characteristics of the tested vehicles during regenerative braking: a–b) in urban driving conditions, c–d) in non-urban driving conditions relative to the supply voltage

erator is proportional to its rotational speed. High speed values result in the higher voltage values. From the energy recovery characteristic it follows that the generated voltage values depend only on the rotational speed and not on the torque. Such a rule applies when changing the voltage from the battery supply voltage (about 240 volts) to 600 volts. Above this value (600–650 volts) the voltage is only obtained for maximum power range generated during braking. These conditions apply to all test route variants used in the study.

d)

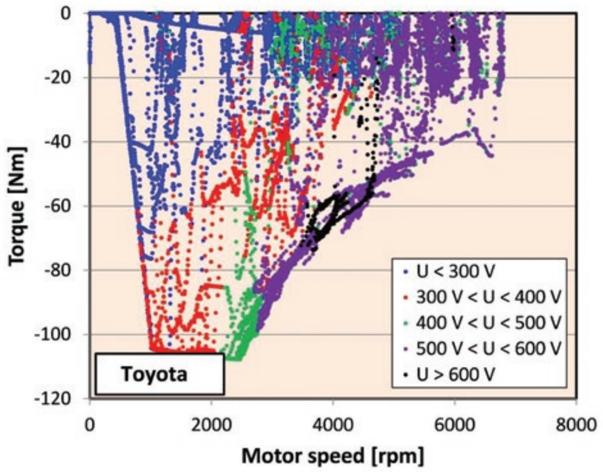


Fig. 5. Electric motor characteristics of the tested vehicles during regenerative braking: d) in non-urban driving conditions relative to the supply voltage

When analyzing the torque value during braking, supplemented by engine rotational speed, it is possible to determine the flow of energy using the equation:

$$E = 2\pi \int_{t=0}^{t=tm} Tndt \qquad (1)$$

where: T – braking torque of the electric motor, n – engine speed.

With this equation the energy during regenerative braking was determined along with the voltage generator divisions into intervals. According to Figure 5 and after application of equation (4) it was found that the largest share of regenerative braking in urban areas is at voltage of up to 300 volts. This represents over 40% of the driving time for the Lexus and over 50% of the Toyota test drives (Figure 6a). It is characteristic that the increased voltage in the Lexus vehicle while recovering energy increases further for greater voltages. This is true for both urban and non-urban driving (Figure 6b).

In urban driving conditions the contribution of higher voltages in the overall operating time decreases. The largest share of voltage in non-urban conditions (around 30% of regenerative braking time) is between 500 and 600 V, which can be explained by increased driving speeds and the ability to process higher kinetic energy values into electricity. As shown in Figure 5, this range applies to the highest electric motor speed during regenerative braking.

5.3. Analysis of the energy flow through the battery in vehicle operation

An important aspect of conducting road tests is the initial charge level of high voltage batteries called SOC (state of charge). It indicates the amount of energy stored in the battery at the start of the test – at the same time it gives information on the possibility of using electric motors without having to start the combustion engine.

The SOC value in both urban and non-urban drives in the study was similar, at approximately 45% (Figure 7). Both drives were characterized by a similar energy flow, as the final battery charge in both cases was comparable. In urban driving conditions, it was about 57% for both vehicles (ΔSOC = 12%). While in non-urban driving conditions the value was higher, at 60% (ΔSOC = 15%). This is another confirmation of the comparability of the test drives made by the two vehicles.

The energy flow conditions were also analyzed, these confirm the similarity of energy flow management in both tested vehicles. The value of energy changes is similar, but the final energy stored in the

a)

b)

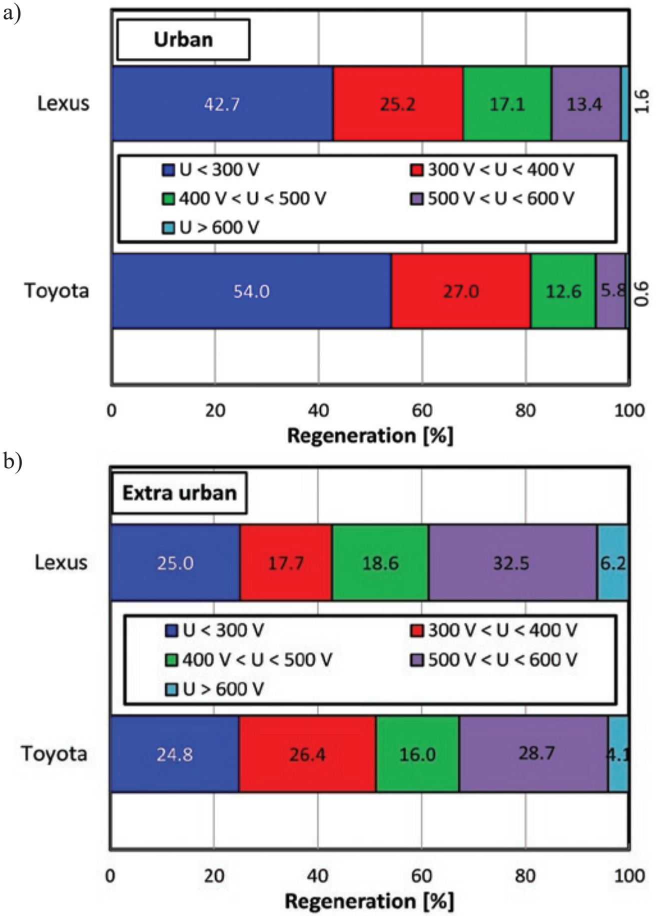


Fig. 6. Analysis of relative energy recovery time shares taking into account the electric generator voltage of the tested vehicles: a) in urban driving conditions, b) in non-urban driving conditions

a)

b)

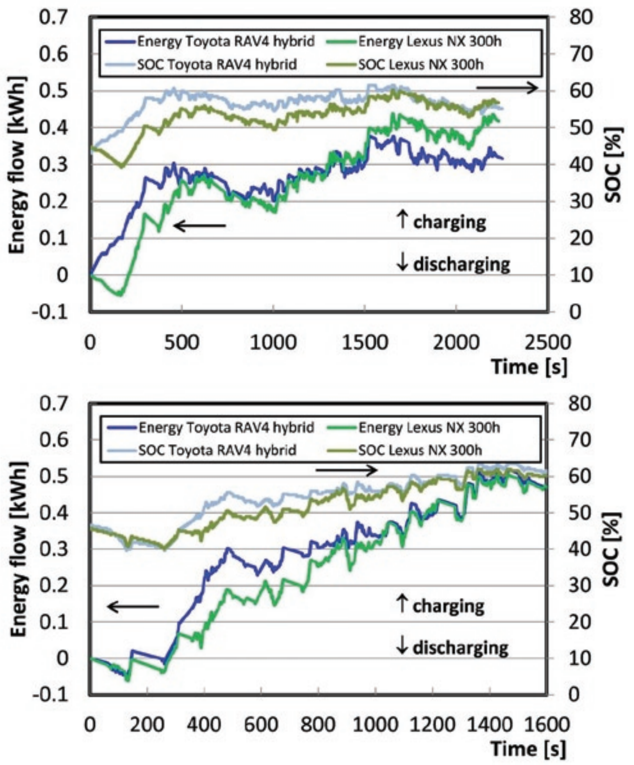


Fig. 7. Analysis of energy flow and battery charge of the vehicles during the drives: a) in urban driving conditions, b) in non-urban driving conditions

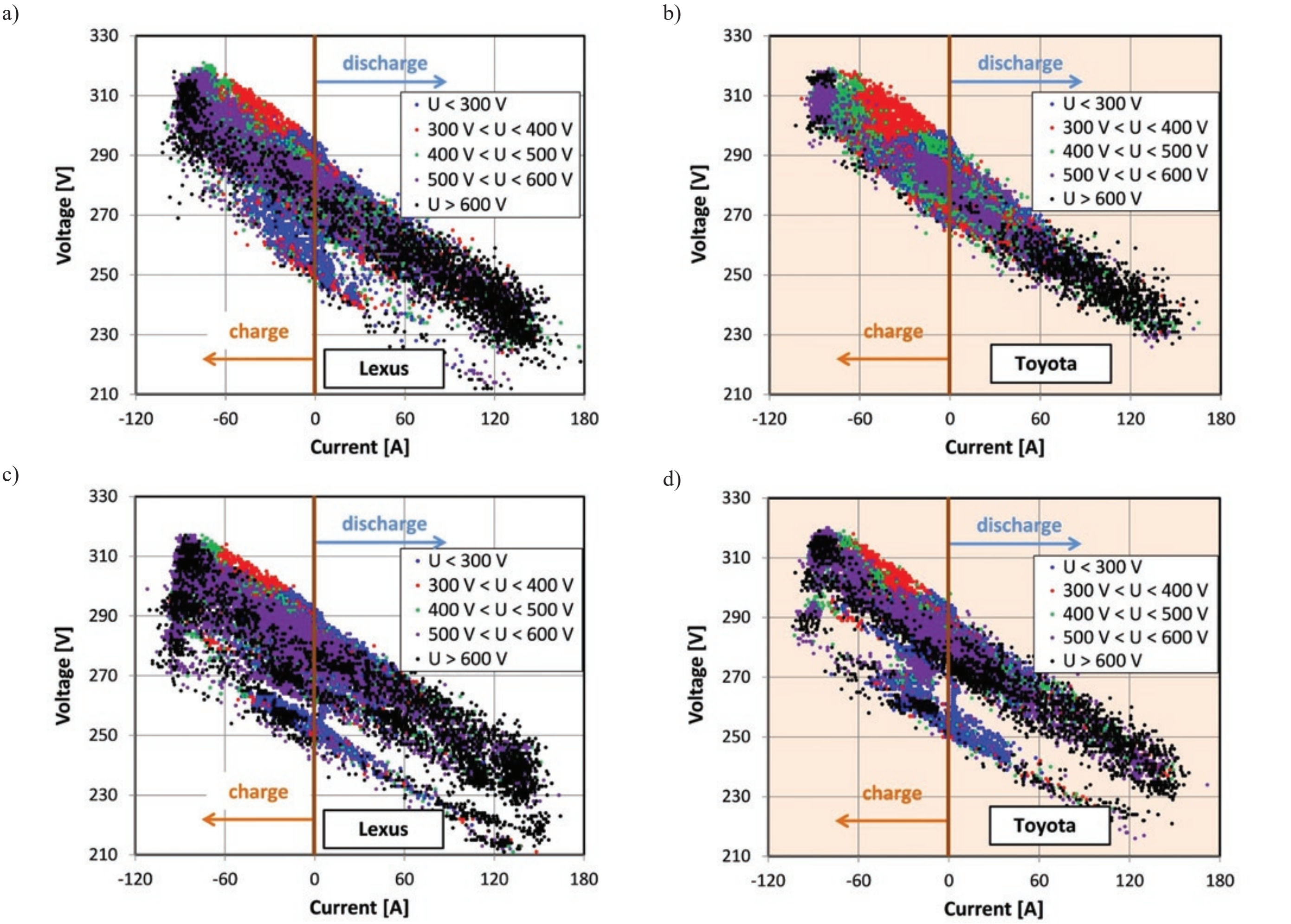


Fig. 8. Charging and discharging voltage characteristics of high-voltage batteries: a–b) in urban driving conditions, c–d) in non-urban driving conditions relative to the supply voltage of the electric motors

battery is greater for the Lexus than for the Toyota. These changes in favor of the Lexus vehicle may result from greater vehicle weight (which is visible in early stages of the drives from the battery discharge rate), but also results in greater braking energy recovery as described by:

$$E = m \int_{t=0}^{t=tm} v dt \quad (2)$$

where the weight of the vehicle affects the value of kinetic energy converted to electricity.

Analysis of SOC changes in urban drive conditions indicates no continuous recharging of the battery to maximum values. At the beginning of the route, after obtaining a SOC of 60%, it is then discharged down to about 50%. Therefore, it has been asserted that the typical SOC values in urban environments oscillates in the range of 50–60%. In non-urban driving conditions, the use of the electric motor's boost mode for the combustion engine is more frequent, indicating a lower battery charge rate. In this case, the battery SOC of 60% was achieved only in the final section of the test drive route, which is typically an urban stretch allowing for increased energy recovery.

4. Analysis of high-voltage battery operation in different driving conditions

Battery performance analysis indicates that higher battery currents and lower voltages relate to battery discharging (Figure 8). Analysis of voltage changes in electric motors during charging and discharging of the battery indicates a certain pattern. The lowest voltage value (less than 300 V) is used at low current flow through the battery. As the current increases, the voltage boost is increased. This is a characteristic feature of these systems, regardless of the direction of current flow (charging or discharging the battery).

5. Energy flow analysis during vehicle operation

The previously analyzed aspects of the eclectic motors and accumulators operating conditions allow making a comparison of the energy flow in hybrid drive systems in road conditions.

The collected measurement data allowed to specify the following phases of energy flow:

- discharge of high-voltage batteries (power drained from the high-voltage battery – $IB > 0$),
- charging in typical conditions (current flow into the battery $IB < 0$ and no regenerative braking $Th < 0$),
- charging with regenerative braking (current flow into the battery $IB < 0$ and negative torque on motor $Th < 0$).

These conditions made it possible to determine the energy values of the three vehicle driving modes. The sum of all energy values al-

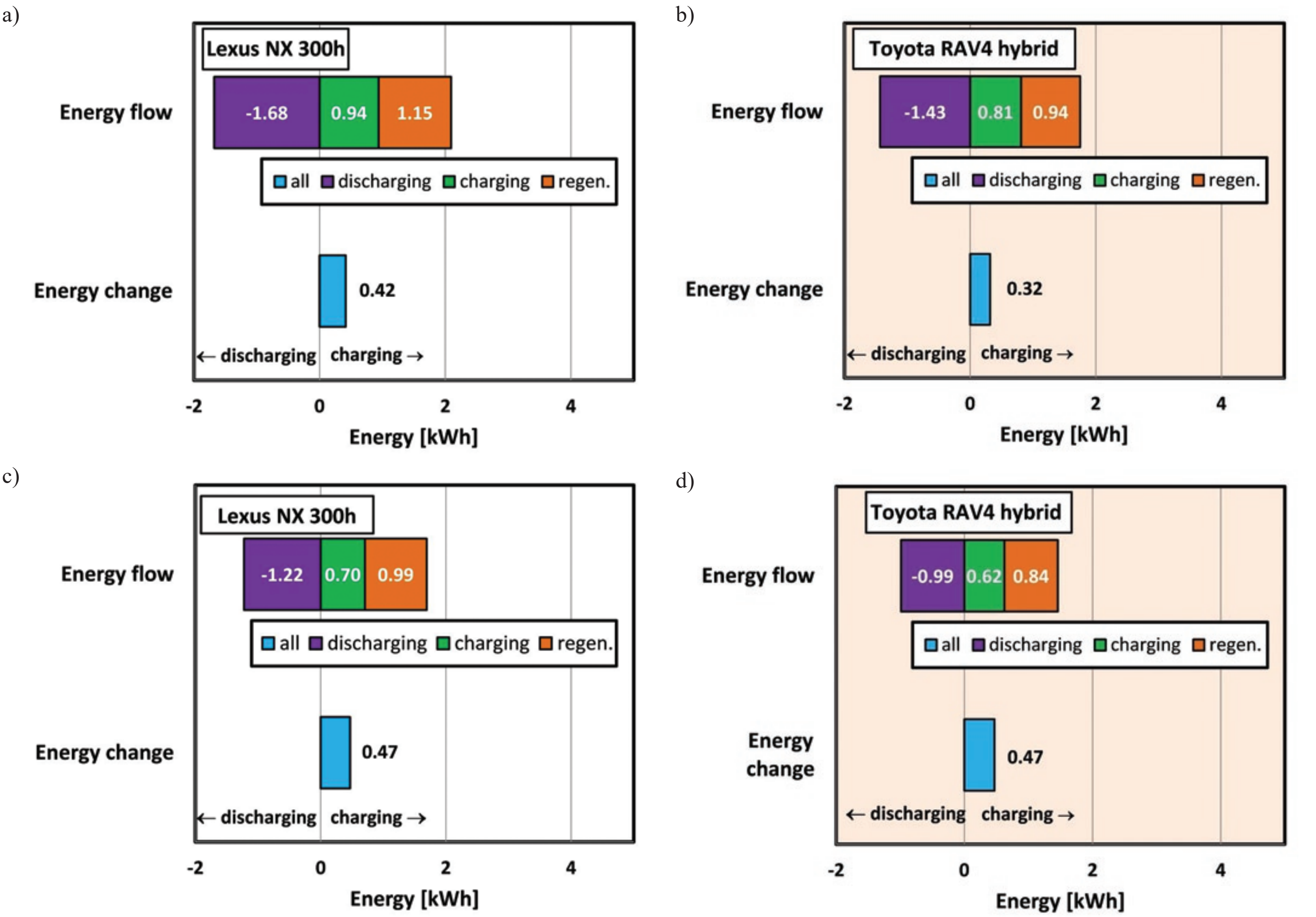


Fig. 9. The energy flow and total change of battery charge analysis during driving: a–b) in urban driving conditions, c–d) in non-urban driving conditions, including charging, high-voltage discharge and regenerative braking

lows to determine the energy changes to the final energy value stored in the battery. In urban driving conditions, the Lexus vehicle (1.68 kWh) had a higher battery discharge rate (15.6%) than in the case of the Toyota (1.43 kWh) battery (Figures 9a and 9b). Similarly, an increased value of recovered energy – 14% higher, was recorded for the same vehicle. Taking into account the battery charging from the internal combustion engine, the battery charge change in the Lexus NX 300h was 0.42 kWh (additional battery charge). In the same urban driving conditions, the change in battery power in Toyota was 0.32 kWh. The 24% greater value of the energy accumulated in the battery is the result of all analyzed values presented above (discharge, charge, regeneration) being higher for the Lexus vehicle.

Non-urban driving analysis shows similar differences in battery discharge – in the Lexus NX 300h this value is 19% higher than for the Toyota RAV4 hybrid (Figure 9c and 9d). Taking into account the fact that the Lexus NX 300h has acquired more energy from battery charging (11%) and energy recovery (5%), the total amount of energy change in batteries was exactly the same (0.47 kWh).

It can thus be stated that in non-urban driving conditions, the amount of extra energy in the battery did not depend on the vehicle type (that is, the weight of the vehicle, since the other parameters are equivalent).

6. Conclusions

An analysis of hybrid vehicles operating conditions leads to the conclusion that their characteristics in urban and non-urban environments are different. This results in different energy flows and the charging and discharging rates of the high-voltage batteries. Detailed conclusions are given below:

- Using this electric motor speed characteristic analysis it can be seen that it is possible to supply the motor with different voltage values at any given rotational speed. This voltage increases with the required torque value. Increasing the supply voltage increases the power of the motor.
- During braking the generator voltage changes in proportion to the rotational speed. High rotational speed results in the highest voltage values. The energy recovery characteristic indicates that the voltage values depend only on the rotational speed and not on the torque.
- Changes in battery charge range vary between 50–60% in the urban driving conditions. In non-urban driving conditions, the electric motor's boost mode is used more, indicating a lower battery charge rate. Battery charge of up to 60% was reached only at the end of the route.
- The battery charge value changes during the test drives are similar, but the final energy accumulated in the battery at the end of the route is greater in the Lexus NX 300h than in the Toyota RAV4 hybrid. These differences in favor of the Lexus vehicle could be caused by different vehicle weights (higher for the Lexus) that affect the amount of kinetic energy converted into electricity.
- The smallest voltage value (less than 300 V) is used at low battery current. As the current increases, the voltage boost is increased. This is a characteristic feature of these systems, re-

gardless of the current flow direction (charging or discharging the battery).

The above studies were carried out with the same level of battery charge in both urban and non-urban drive conditions. The next stage of this research is the operational analysis of such drives with respect to the different initial conditions of stored energy in the batteries of these vehicles. This way the characteristics of these drives should be significantly different.

References

1. Hu X, Jiang J, Egardt B, Cao D. Advanced power-source integration in hybrid electric vehicles: multicriteria optimization approach. IEEE Transactions on Industrial Electronics 2015; 62 (12): 7847–7858, http://dx.doi.org/10.1109/TIE.2015.2463770.
2. Hu X, Moura S J, Murgovski N, Egardt B, Cao D. Integrated optimization of battery sizing, charging, and power management in plug-in hybrid electric vehicles. IEEE Transactions on Control Systems Technology 2016; 24 (3): 1036–1043, http://dx.doi.org/10.1109/TCST.2015.2476799.
3. Kasprzyk L. Modelling and analysis of dynamic states of the lead-acid batteries in electric vehicles. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2017; 19 (2): 229–236, http://dx.doi.org/10.17531/ein.2017.2.10.
4. Li L, Wang X, Xiong R, He K, Li X. AMT downshifting strategy design of HEV during regenerative braking process for energy conservation. Applied Energy 2016; 183: 914–925, http://dx.doi.org/10.1016/j.apenergy.2016.09.031.
5. Merkisz J, Pielecha I. Układy mechaniczne napędu hybrydowego. Wydawnictwo Politechniki Poznańskiej, Poznań 2015.
6. Michel P, Charlet A, Colin G, Chamaillard Y, Bloch G, Nouillant C. Optimizing fuel consumption and pollutant emissions of gasoline-HEV with catalytic converter. Control Engineering Practice 2017; 61: 198–205, http://dx.doi.org/10.1016/j.conengprac.2015.12.010.
7. Navamani J D, Vijayakumar K, Jegatheesan R. Non-isolated high gain DC-DC converter by quadratic boost converter and voltage multiplier cell. Ain Shams Engineering Journal 2016, in press, http://dx.doi.org/10.1016/j.asej.2016.09.007.
8. Pielecha J, Merkisz J, Markowski J, Jasinski R. Analysis of passenger car emission factors in RDE tests. E3S Web of Conferences 10, UNSP 00073 (2016), http://dx.doi.org/10.1051/e3sconf/20161000073.
9. Stroe N, Colin G, Ben-Cherif K, Olaru S, Chamaillard Y. Towards a generic control-oriented model for HEV predictive energy management. IFAC 2016; 49 (11): 259–264, http://dx.doi.org/1.1016/j.ifacol.2016.08.039.
10. Tani A, Camara M B, Dakyo B, Azzouz Y. DC/DC and DC/AC converters control for hybrid electric vehicles energy management-ultracapacitors and fuel cell. IEEE Transactions on Industrial Informatics 2013; 9 (2): 686–696, http://dx.doi.org/10.1109/TII.2012.2225632.
11. Wei Z, Xu J, Halim D. HEV power management control strategy for urban driving. Applied Energy 2017; 194: 705–714, http://dx.doi.org/10.1016/j.apenergy.2016.10.023.
12. Wei Z, Xu Z, Halim D. Study of HEV power management control strategy based on driving pattern recognition. Energy Procedia 2016; 88: 847–853, http://dx.doi.org/10.1016/j.egypro.2016.06.062.
13. Zhu L, Yu F R, Ning B, Tang T. Optimal charging control for plug-in electric vehicles in smart microgrids fueled by renewable energy sources. International Journal of Green Energy 2013; 10 (9): 924–943, http://dx.doi.org/10.1080/15435075.2012.727364.

Ireneusz PIELECHA
Wojciech CIEŚLIK
Institute of Combustion Engines and Transport
Poznan University of Technology
ul. Piotrowo 3, 60-965 Poznań, Poland

Andrzej SZAŁEK
Toyota Motor Poland
ul. Konstruktorska 5, 02-673 Warszawa, Poland

E-mails: Ireneusz.Pielecha@put.poznan.pl,
Wojciech.Cieslik@put.poznan.pl, Andrzej.Szalek@toyota.pl