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Energy recovery potential through regenerative braking for a hybrid electric vehicle in a urban conditions

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Abstract. Vehicles with hybrid drive systems are being equipped with solutions that increase the drive systems efficiency more and more often. One such solution is the energy recovery during braking. Additionally this process leads to a voltage increase of the energy recovering generator. Battery voltage is increased several times in the inverter system in order to increase the electric generator power. The article presents the possibility of such a voltage gain from vehicle braking in urban driving conditions. The latest models of vehicles with hybrid drive systems were used in the tests, equipped with the same drive units, these were: Lexus NX 300h and Toyota RAV4 Hybrid. These are vehicles equipped with parallel hybrid drives (full hybrid). The tests were performed in an urban environment in the city of Warsaw, on the same routes. The study analyses the startup conditions of such a system and the characteristics of its operation. It has been shown that the increase in the voltage powering the electrical machinery occurs in both vehicles at high torque values. It has also been shown that rise in electrical equipment voltage for both of these vehicles mostly depends on their engine speed, and not on the generated power or torque (braking). The maximum voltage increase—almost threefold (up to 650 V) also allows for a two-fold increase in the drive system breaking torque.

1. Introduction

Limiting the negative environmental impact of vehicles is associated with an ongoing effort to reduce fuel consumption. One of the options for reducing fuel consumption and emissions is the use of hybrid powertrain systems. Probably with the further emission restrictions imposed by the introduction of the Euro 7 emission standard, most of the passenger car manufacturers will retire from diesel engines entirely, and the most common method of meeting the strict new emissions standards will be the production of hybrid vehicles [1]. The variety of applications of these drives makes them a popular substitute for conventional motor vehicle drive systems. This is particularly important in countries where drivers experience the benefits of using them, for example in the form of reduced taxes on vehicle purchase, access to city centers or free parking space. Conventional vehicle testing requires only the determination of emission levels under laboratory [2] or road conditions using PEMS (Portable Emission Measurement System) [3]. In addition to emission tests [4], the testing procedures of hybrid power systems [5–7] also requires power management system tests.

One of the most important components of the hybrid drive, apart from the diesel-electric drive unit, is a high-voltage battery. Nickel-Metal Hydride (NiMH) batteries were used in about 95% of hybrid

vehicles in their early development period [8]. The voltage of a single cell is about 1.3 volts and the actual specific energy is 75 Wh/kg (about 240 Wh/dm^3) [8].

Lithium-ion batteries have a cell voltage of about 4 volts and their energy density is 180 Wh/dm^3 [8]. The efficiency of these batteries is quite varied: the lowest values are for lead acid (75–85%) and nickel-hydride (65–85%), and the largest—lithium-ion (90–94%) [8].

Comparison of NiMH and Li-Ion Battery performance by Kang et al. [9] allows to state that the state of charge (SOC) has little effect on their change in efficiency when increasing the discharge current. The efficiency of Li-Ion batteries is about 97% (at a charging current of 1C – capacity) to 93% (at 5C). Analogous operating conditions of NiMH batteries result in an efficiency value of 95% to 91%. In this paper it was also found that the battery charge level has little impact on its efficiency. Research on Li-Ion batteries indicates the highest efficiency on SOC of 40–60%, whereas for NiMH batteries it is in the value range of 30–50%. When discharging batteries, the highest efficiency is with SOC of 80–100% (Li-Ion) and 70–80% (NiMH).

Different methods of determining and estimating the SOC of batteries have been presented by Waag [10], concluding that these methods are suitable for estimating the capacity of new batteries. When analyzing used or older batteries other battery parameters must be taken into account (including the influence of ambient temperature change on battery resistance). Different SOC measurement methods proposed by Liu et al. [11] are based on the Extended fractional Kalman filter. Consequently, Liu et al. [11] stated that this method can be used by the battery management system (BMS) to increase their operating parameters when managing batteries.

Hannan et al. [12], in the paper presenting the energy management system analysis, presented a hybrid vehicle energy management scheme based on the battery SOC. The authors have identified several operating parameter ranges for such a battery depending on the power demand on the wheels of the vehicle (figure 1).
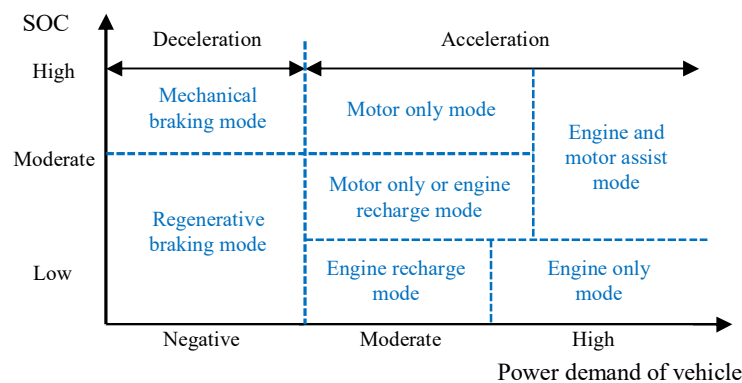

Figure 1. Energy management system operation chart on PHEV [11].

One of the ways to increase the power of a hybrid drive is to boost the voltage supplied to the motor (or motors).

Voltage boost is defined as the value of the voltage supplied to the electric motor (U_mot) over the value of the battery voltage (U_bat):

$$\text{boost} = \text{U\_mot} \cdot \text{U\_bat}^{-1} \ [–] \qquad (1)$$

Current hybrid drive solutions, despite using batteries rated at between 200 V and 250 V, allow for powering of electric motors at 650 V (figure 2). This gain of the motor input voltage allows increasing the maximum voltage value by a factor of 2.5–3.
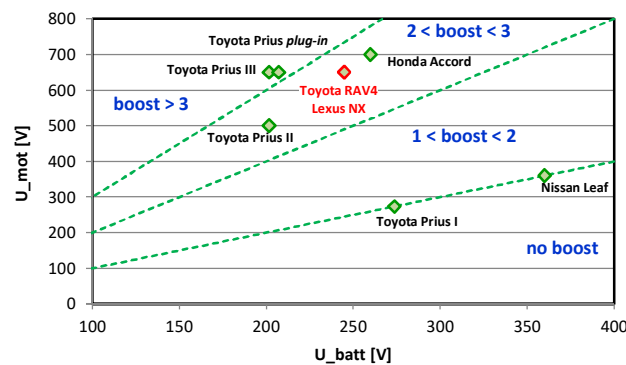
Figure 2. Solutions of voltage boosting systems for electric motors.

2. Aim of the research

Although the values of the maximum boost of voltage supplied to the electric motor of the hybrid vehicle are well known, the voltage values during regenerative braking still require proper assessment. These values should be variable relative to the values of the recovered electrical power during regenerative braking.

The aim of this article is to determine the operating conditions of the hybrid drive electrical system during regenerative braking in urban conditions. These conditions were chosen because of the significant contribution of the braking activity to the overall driving time. In addition, the tests were carried out on two vehicles equipped with the same hybrid drive system to determine changes resulting only from the differences in the vehicle mass (and possibly hybrid system drivers).

3. Description of research objects

The use of energy management in hybrid vehicles was based on the study of two vehicles equipped with the same hybrid system: Toyota RAV4 hybrid and Lexus NX 300h. Vehicles were equipped with a four-wheel drive: front—hybrid, rear—electric. Both vehicles were equipped with NiMH batteries with a nominal voltage of 244.8 V. The differences in the two test vehicles were the vehicle mass, with Toyota RAV4 hybrid at 1735 kg, whereas the Lexus NX 300h was over 100 kg heavier at 1860 kg (table 1).

Table 1. Technical specification of the tested vehicles.

Parameter	Unit	Toyota RAV4 hybrid	Lexus NX 300h
Engine			
Displacement	dm^3	2,494	
Torque	Nm @ rpm	206@4400–4800	
Power	kW @ rpm	114@5700	
Electric propulsion—front			
Torque	Nm @ rpm	270@0–1800	
Power motor	kW @ rpm	105@4500	
Electric propulsion—rear			
Torque	Nm	139	
Power motor	kW	50	
Energy storage			
Energy	kWh	1.59	
Battery voltage	V	244.8	
Max inverter voltage	V	650	
Vehicle			
Mass	kg	1735	1860

4. Testing conditions

Hybrid drive research tests were conducted using the so-called "follow the leader" style (one after the other). Due to the organization of the traffic only partial repetitiveness of the traffic conditions is observed (figure 3). The maximum speeds achieved by vehicles differ by 6 percentage points. Other drive characteristics parameters are more similar. The time share of acceleration for the two vehicles was very similar (about 35%), the braking time share is about 30%. Vehicle stops lasted about 22–24%. These values of drive parameters make it possible to recognize them as reproducible and the tests conducted in a way that allows for comparing results.

The study was conducted in urban drive conditions in the urban agglomeration, on a typical working day. The test drive distance was about 14,900 m, and the drive lasted about 2250 s. The average speed in urban traffic was approx. 24 km/h.
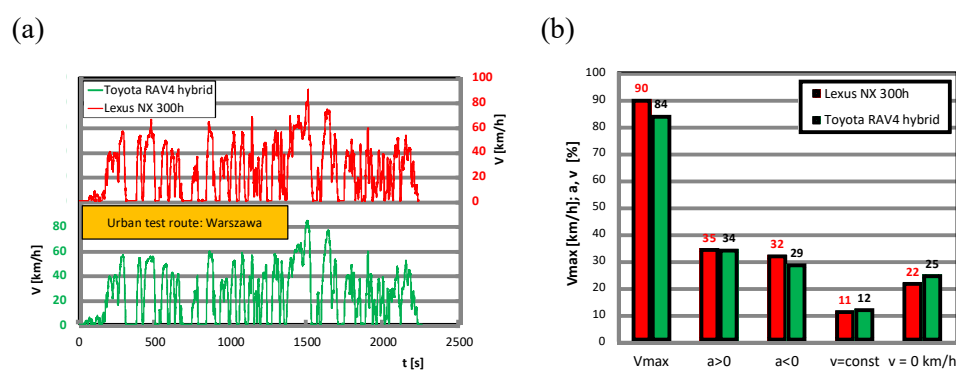
(a)   (b)

Figure 3. Test conditions: comparison of routes (a), repeatability analysis (b).

The similar conditions of the urban test route in both drives resulted in similar energy recovery values for the vehicles. Energy recovery takes place mainly during braking. However, the data analysis in figure 4 indicates that the energy recovery stops at a vehicle speed of about 7 km/h and below. This is due to the need to use the classic braking system to completely stop the vehicle. Energy recovery in the Lexus NX 300h vehicle had a time share of about 20% of the entire route, while in the Toyota RAV4 hybrid – 15% of the route.
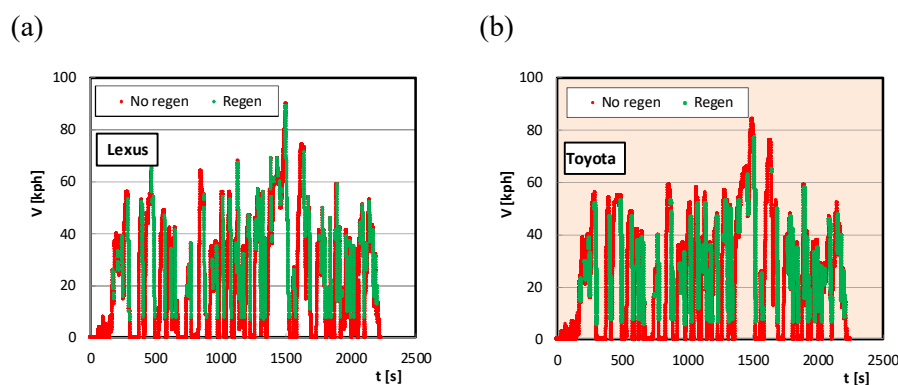
(a)   (b)

Figure 4. Test conditions: Lexus NX 300h (a), Toyota RAV4 hybrid (b).

5. Analysis of the regenerative braking conditions of a hybrid vehicle

The regenerative braking conditions shown in figure 4 are analyzed relative to the braking torque magnitude. Although the maximum torque of the electric motors (front wheel drive) is 270 Nm, the recorded braking torque was only 110 Nm (figure 5). This value is the same for both the Toyota RAV4

hybrid and the Lexus NX 300h. It should be noted that with the electric motor speed reduction during regenerative braking, the voltage boost is limited. Voltages above 600 V for the braking of both of the vehicles appear only on external characteristics in the engine speed range of 3500–5000 rpm. The range of flat–maximum torque values on the electric motor speed characteristics includes voltage value range from less than 300 V up to 500 V. In this range of torque values voltage greater than 500 V does not occur, which means that the voltage boost does not exceed the factor of 2.
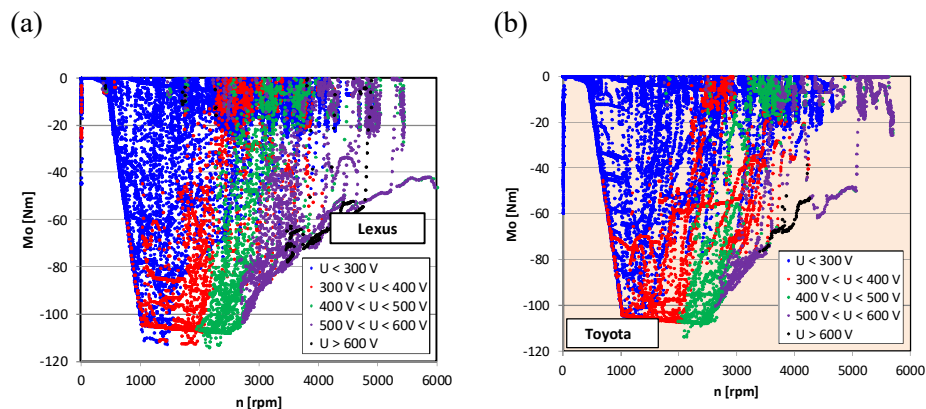
(a)   (b)

Figure 5. Regenerative braking characteristics, taking into account voltage values for: Lexus NX 300h (a), Toyota RAV4 hybrid (b).

Analysis of the same braking conditions taking into account the voltage boost factor generated during braking indicates that a large area of the motor characteristic corresponds to a boost factor value in the range of 1 to 2 (figure 6). Boosting the voltage by more than a factor of 2 occurs practically only at high rotational speed of the motor. These are the operating points of the electric generator corresponding to the maximum power of the system.

There is no difference in the operating conditions of both vehicles. In Lexus NX 300h, boost factor exceeds 2 (boost > 2) only slightly more often than that of the Toyota RAV4 hybrid. The characteristics of using voltage without boost are very close to each other. These include small values of motor rotational speed, which corresponds to a low electric generator power.
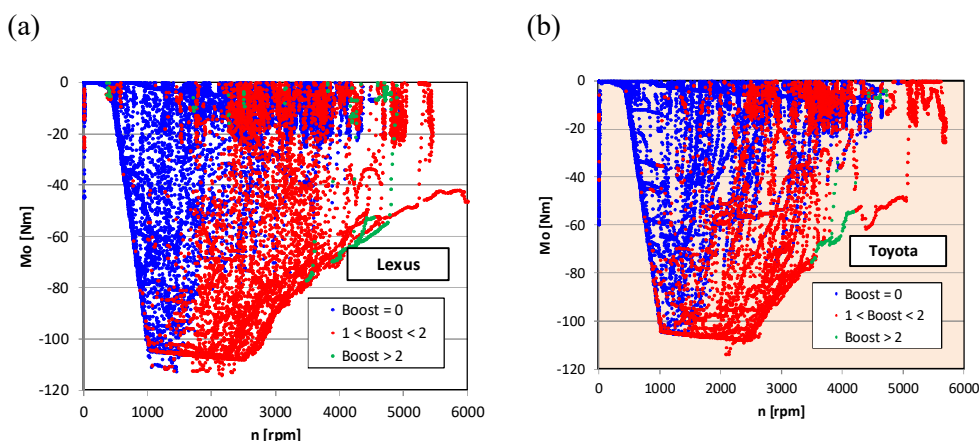
(a)   (b)

Figure 6. Regenerative braking characteristics taking into account voltage values: Lexus NX 300h (a), Toyota RAV4 hybrid (b).

Analyzing the braking torque value (Mo), supplemented by the rotational speed readings (n), it is possible to determine the value of power ($Mo \cdot 2\pi n$)and energy flow (E) using the equation:

$$E = \int_{t=0}^{t=tm} Mo \cdot 2\pi n \, dt \qquad (2)$$

Energy during battery charging, during discharge and during regenerative braking was determined on this basis. In addition, the sum of the changes in the energy flow was determined taking into account the flow direction (to or from the battery), which is shown in figure 7.

Comparative analysis of driving conditions shows that, during a drive on the same route, the Lexus batteries have been charged more than the Toyota RAV4 hybrid batteries. This difference in charge is 25% in favor of the Lexus NX 300h (0.4 kWh versus 0.32 kWh). Hence the analyzed urban traffic allows for charging of a high voltage battery, which is conducive to frequent vehicle braking.

Analysis of regenerative braking conditions indicates that the Lexus NX 300h recovered about 22% more energy in this driving mode than the Toyota RAV4 hybrid (1.15 kWh compared to 0.94 kWh). Higher energy recovery values also allow for its use, with the Lexus NX 300h driving system delivering 1.73 kWh and the Toyota RAV4 hybrid 1.43 kWh. It follows that the Lexus NX 300h used 21% more battery power than the RAV4 hybrid.
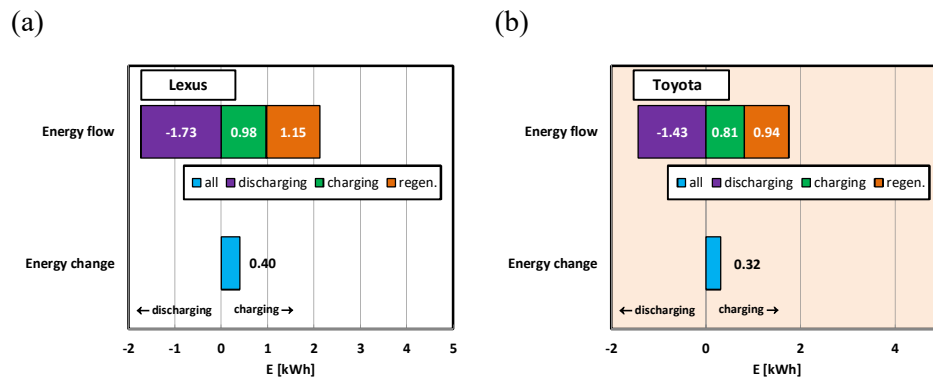

Figure 7. Analysis of energy flow while driving in urban conditions with vehicles: Lexus NX 300h (a), Toyota RAV4 hybrid (b).

The amount of energy recovered by Lexus and Toyota vehicles was analyzed in terms of voltage boost. It was found (figure 8) that the time share of regenerative braking in the absence of voltage boost is the same for both vehicles (0.30 kWh). The share of recovered energy in the Lexus NX 300h is approximately 32% higher. It should be noted that for both vehicles, the share of recovered energy at the voltage boost factor between 1 and 2 is twice as high as in the absence of such boost. The share of voltage boost with a factor above 2 is negligible. It represents about 10% of the energy value obtained without voltage boost. This means that it is possible to recover twice as much power than it was possible in the absence of such boost (while keeping the same current).

A summary of the results of studies and analyzes of energy recovery in urban agglomeration traffic conditions show similar amounts of recovered energy in the absence of voltage boost. The biggest discrepancies occur when boosting by the factor between 1 and 2. Differences are 20 percentage points in favour of the Lexus NX 300h. This may be in part due to the greater weight of the vehicle (m), as the kinetic energy of braking (E) is defined by the equation:

$$E = m \int_{t=0}^{t=tm} v \, dt \qquad (3)$$

This formula contains the vehicle mass (m) which affects the change in kinetic energy.
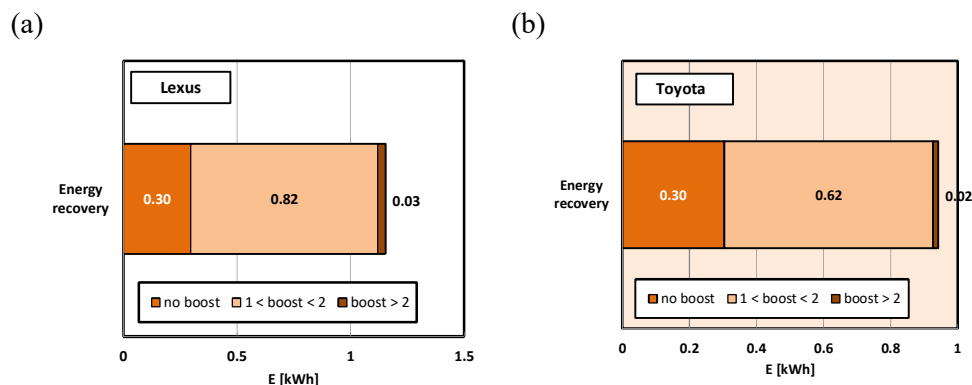
Figure 8. Analysis of energy recovery while driving in urban conditions with vehicles: Lexus NX 300h (a), Toyota RAV4 hybrid (b).

However, it should be noted that the difference in vehicle mass is about 7% and the difference in energy recovery is over 30% (figure 9a). It follows that the amount of energy recovered is not only affected by difference in mass. In addition, these differences in results may be caused by the urban traffic conditions and different time densities and intensity of regenerative braking. Similar differences are also found in the analysis of the voltage values obtained behind the inverter. These differences are not great, but in the case of the Lexus NX 300h, the range of regenerative braking power at 400–500 V is much higher than that of a Toyota RAV4 hybrid. The largest amount of recovered energy corresponds with the voltage below 300 V (with little or no boost).
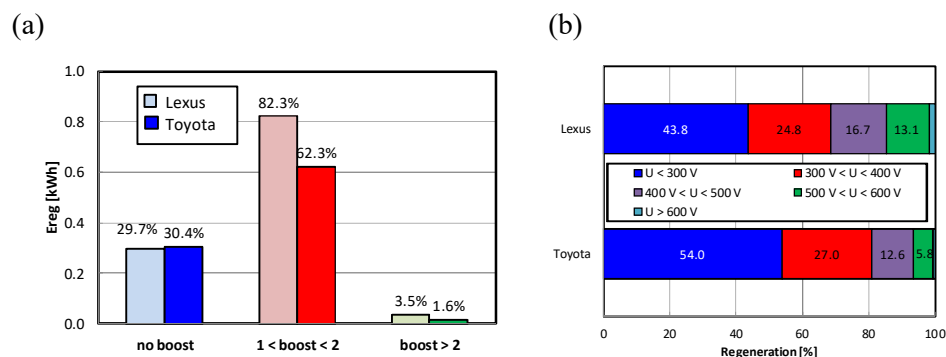

Figure 9. Comparative analysis of energy recovery conditions: with respect to the voltage boost (a), the energy recovery time densities with respect to the boosted voltage (b).

6. Summary

Analysis of the research results and conducted analyzes of energy recovery from hybrid vehicles in driving conditions of an urban agglomeration lead to the statement that the entire range of the available boost system voltages is used.

A detailed analysis of this issue points to the following conclusions:

1. High voltage regeneration braking occurs at high generator speed, which means that it happens in the initial braking phase. This value mostly occurs on the external generator torque characteristics. In this range the voltage boost factor is greater than 2.

2. During regenerative braking, the value of the voltage boost is usually within the range of <1,2>. In this range, on the external characteristics of maximum braking torque, voltage values are in the range of <244 V,500 V>. This means no boost or a boost factor of up to 2.

3. Drive in urban traffic conditions allows for a positive SOC change. The increase in battery power ranged from 0.32 kWh (for Toyota RAV4 hybrid) to 0.40 kWh (for Lexus NX 300h). In the case of the Lexus vehicle, the achieved energy recovery value was 22% higher than for the Toyota. This, along with the typical recharging of the battery, increased the total energy discharged from the battery by 21%.

The authors plan to conduct the next stage of this research to determine the impact of regenerative braking in hybrid vehicles onthe exhaust emissions and fuel consumption. This analysis will contribute to the assessment of the environmental benefits of using HV vehicles in both urban and non-urban traffic.

Symbols and abbreviations

a	acceleration
C	capacity
E	energy
I	current
Li-Ion	lithium-ion battery
Mo	torque
n	speed
NiMH	nickel-hydride battery
SoC	state of charge
t	time
U	voltage
U_mot	voltage of motor
U_bat	voltage of battery
V	vehicle speed
$Vmax$	maximum vehicle speed

Acknowledgements

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