Determination of the combined power source parameters in a hybrid small class share taxi based on modelling energy consumption process

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Abstract. The study aims to analyze and assess the efficiency of a combined power source of a city share taxi under the Russian climatic conditions. The article considers the main types of hybrid vehicles and determines the most suitable scheme for the operation of small-tonnage vehicles in urban traffic cycle. Optimal values of the power of the primary energy source and the energy intensity of a buffer energy storage are calculated. A model has been synthesized that allows refining the data obtained, as well as to determine fuel consumption, the share of the internal combustion engine operating time, and the depth of the discharge of the energy storage unit when the vehicle is moving in a given driving cycle. As a result, it has been found that the minimum energy intensity makes up 150 Wh, the power of the primary energy source equals 27 kW, the fuel consumption is equal to 5.79 l/100 km, and the percentage of the enabled internal combustion engine makes up 29% for a city minibus which has 3.5 tons.

1. Introduction
In Russia, the development of electric vehicles is becoming more important. Statistics show that the number of purchased hybrid and electric cars has grown for the last three years [1]. According to the innovative development scenario represented in the Transport Strategy of the Russian Federation, the hybrid and all-electric car share can reach 30% by 2030 [2].

The using of all-electric vehicles is complicated in Russia. Lithium-ion batteries (LIB) used in electric cars have a strict limit in the range of permissible temperatures. Thus, at temperatures below 0°C, a significant drop in lithium batteries power occurs, which limits the dynamics of the vehicle and does not allow effective energy recovery during braking [3]. Significant amounts of energy are also dedicated to maintaining a comfortable temperature inside the cabin, being that the average annual temperature of the Russian regions is close to or below 0°C [4].

Due to the high cost of kWh LIB and low specific energy consumption, increasing of the energy storage unit (ESU) for own needs and heating the battery is not practical. It is reasonable to use hybrid electric vehicles (HEV), in which the primary energy source based on the internal combustion engine during operation recharges and heats the ESU at the same time, which ensures the dynamics of the vehicle [5].

2. Hybrid power source configuration analysis
Varieties of an HEV are represented by series (Figure 1, a), parallel (Figure 1, b) and series-parallel schemes (Figure 1, c). The serial scheme is the simplest hybrid configuration. ICE is used only...
to drive a generator. Generated electricity charges ESU and feeds electric motor (EM), which rotates drive wheels. This configuration eliminates the need for gearbox and clutch. Regenerative braking is also applied to recharge a battery. The serial configuration allows using low-power ICEs sufficient to provide energy to drive. At the same time, the ICE constantly works at the range of maximum efficiency or turns off when the ESU is fully charged. When the ICE is turned off, the EM and ESU can provide the necessary power for driving. Therefore, they, in contrast to ICE, should have relatively large power.

![HEV configurations](image)

**Figure 1** — HEV configurations, a) series, b) parallel, c) series-parallel.

The series circuit is most effective for frequent partial braking during driving, braking and acceleration, driving at low speed, i.e. in the urban. Therefore, this type of hybridization is used in city buses and other forms of urban transport. Large mining dump trucks also work on this principle, where they is necessary to transfer large power.

Unlike the series circuit, the parallel circuit allows setting the vehicle in motion using two power sources. The main advantages of the parallel circuit are lower EM power and the lack of multiple power conversion from ICE to drive wheels. However, due to the mechanical connection of ICE with wheels, the overall control becomes more complicated [6].

The series-parallel hybrid configuration combines the features of two previous types. A separate generator and a power divider (a planetary gear) are added to the parallel hybrid circuit. As a result, the HEV acquires the features of a series hybrid, namely: the vehicle starts and moves at low speeds only due to electric traction. At high speeds and when driving at a constant speed, the ICE is connected. At high loads (acceleration, uphill movement), the EM is additionally powered by a battery and the hybrid works as a parallel configuration. Due to the presence of a separate generator that charges the ESU, the EM is used only for wheel drive and regenerative braking. The planetary gear transfers part of the ICE power to the wheels, and the rest to the generator, which either powers EM or charges ESU. The computer system constantly adjusts the power supply from both energy sources for optimal operation under all driving conditions. In this type of hybridization, the EM works most of the time, and ICE is used only in the most effective modes. Hence, the EM power can be lower than in a parallel hybrid. Disadvantages of serial-parallel hybrid include a higher cost, since it needs a separate generator, a larger battery pack, and more complex control system.

As an object of the study, a GAZelle City model small-capacity city minibus with the parameters presented in table 1 was selected [7]. In this case, it is rational to use a series type of hybridization suitable for operation in urban driving mode. The main components of a series hybrid are EM, ICE as a primary energy source (PES) and ESU. The principle of power source operation as follows: ICE recharges ESU through the generator and supplies energy for own needs (dashboard lights, lighting, air conditioning). ESU supplies energy to the engine and receives it during regenerative braking.

The energy flow diagram for a series power source is shown in Figure 2. \( E_{fuel} \) is the energy used fuel; \( E_{ICE}, E_{IG}, E_{ESU}, E_{IC}, E_{LEM} \) are losses in ICE, a generator, ESU, a converter, and EM respectively; \( E_{own} \) is the energy spent on own needs; \( E_W \) is the energy to overcome traction resistance; \( A_D \) is the traction work, divided into the kinetic energy \( E_k \) and the potential energy \( E_p \).
Hydrocarbon fuel is burnt in the ICE, resulting the mechanical energy is fed to the generator that charges the ESU. Further, the energy is consumed by the TED for traction, while part of the energy is returned to the ESU during regenerative braking.

![Image of energy flows in series hybrid power source.](image)

**Figure 2** – Energy flows in series hybrid power source.

| Table 1. GAZelle City parameters. |
|----------------------------------|
| **Value** | **Dimension** |
| Weight | 3.5 ton |
| Number of places | 22 |
| ICE type | ISF2.8s4R129 |
| Fuel type | Diesel |
| Maximum power | 120 h.p. |
| Maximum torque | 295 (2700) N·m (rpm) |
| Fuel consumption | 8.5 l |

3. **Calculation of hybrid source parameters**

Unlike classical transport, where the ICE must provide both dynamic parameters of the vehicle and perform useful work, the dynamics of transport with the series hybridization is ensured by ESD. Thus, the power of ICE should be sufficient to provide energy for the entire motion time and cover own needs losses. The own needs power \((P_{own})\) of buses and trolleybuses can exceed 30 kW, and more than 80% it is determined by maintaining the microclimate of the vehicle [8]. A significant advantage of HEV over pure electric vehicles is the possibility of the heating cabin through the combustion of fuel in ICE.

The required power of PES is determined from the most difficult driving conditions:
- maintaining uniform motion with a maximum vehicle speed at the current slope;
- motion with alternating acceleration to maximum speed and braking when the energy given per cycle is the maximum value.

For the first condition, the specific power of PES is determined by the product of the maximum speed of the vehicle and corresponding traction resistance:

\[
P_{PES1} = \frac{g \cdot w(V_{\text{max}}) \cdot V_{\text{max}}}{3600}, \text{ kW/ton}
\]

where \(g\) is gravitational acceleration; \(w(V_{\text{max}})\) is traction resistance; \(V_{\text{max}}\) is the maximum speed of vehicle.

In the second case, the power of the PES is determined by the most severe motion mode. A standard WLTC driving cycle is adopted as a reference. The difference between the energy expended and obtained as a result of acceleration and deceleration cycle must be compensated by the energy.
supplied from ICE. Otherwise, a critical situation arises when BSU energy is insufficient to maintain the dynamics of subsequent acceleration. The average specific power is determined from the ratio:

$$P_{PES} = \frac{3.6 \cdot (E_{tr} - E_{rec})}{T_{cycle}}, \text{ kW/ton}$$

(2)

where $E_{tr}$ and $E_{rec}$ are energy spent on traction and recovered during braking per cycle, Wh/ton; $T_{cycle}$ is the total driving cycle time, sec.

Given the efficiency of all system elements and own needs losses, the full power of the ICE is determined from the ratio:

$$P_{ICE} = \frac{1}{\eta_G \cdot \eta_{ESU}} \left( P_{own} + \frac{G_T \cdot \max\{P_{PES1}, P_{PES2}\}}{\eta_{EM} \cdot \eta_{mech.gear}} \right), \text{ kW}$$

(3)

where $G_T$ is vehicle weight, ton; $P_{PES1}, P_{PES2}$ are specific power of PES obtained from the first and the second restrictions, kW/ton; $\eta_G$ is the generator efficiency; $\eta_{ESU}$ is the ESU efficiency; $\eta_{EM}$ is the EM efficiency; $\eta_{mech.gear}$ is the mechanical transmission efficiency.

ESU is calculated from the volume of maximum energy consumed during the vehicle motion, considering the operation of PES. Thus, the minimum required energy intensity of ESU is determined by the ratio:

$$A_{ESU} = A_0 + \int_0^{T_{cycle}} (P_{EM} - P_G) \, dt, \text{ kW \cdot h/ton}$$

(4)

where $A_0$ is the stored energy value at initial time; $P_{EM}, P_G$ are power realized by the EM and the generator.

From the ratio follows that with increasing of the PES power, the required ESU energy intensity is significantly reduced. However, with a significant increasing of the ICE power, the need for hybridization disappears. A graph of the required ESU power intensity depending on the generator power is shown in Figure 3.

It follows from the graph that the increasing of the generator power is optimal for WLTC 2 and 3 classes up to 6500 W/t. A further power increasing reduces the energy intensity of ESU in a small amount.

![Figure 3 - Dependence of required ESU energy intensity on power of generator.](image-url)
4. HEV power source simulation
In order to confirm the data obtained by calculating power source main parameters, a model of vehicle power source was synthesized (Figure 4). The resulting model in MATLAB Simulink software includes:

- Installed EM efficiency function subsystem depending on the realized moment and shaft rotation speed;
- ICE efficiency function subsystem with depending on realized power. It also calculates the amount of fuel consumed during the cycle;
- Realized power of EM subsystem depending on speed and acceleration of the driving cycle;
- ESU stored energy subsystem.

**Figure 4** – Series hybrid power source model.

**Subsystem "S1".** In the subsystem (Figure 5), traction and braking EM power is calculated based on the cycle specified by speed and acceleration. It also calculates the range $L$, traction resistance $f(u)$, and force necessary to realize cycle acceleration.

**Figure 5** – Subsystem “S1”.

**Subsystem "S2".** In the subsystem (Figure 6), the overall system efficiency is calculated. First of all, the realized traction force is recalculated to moment and speed of vehicle recalculated into motor’s shaft rotation speed. The obtained moment and speed values are sent to Lookup Table (n-d)” “(M, w)” block, where EM efficiency is determined. Then it is multiplied with the pulse converter efficiency and the mechanical transmission efficiency.
Subsystem "S2". In the subsystem (Figure 7), the EM power is calculated, which is realized in the traction and braking mode.

Subsystem "S3". The EM power obtained in "S1" is supplied to the subsystem “S4” (Figure 8) for calculating energy consumed from ESU. The ratio utilized to determine the energy stored in ESU:

\[ A_{ESU} = A_0 + \int_0^{T_{cycle}} P_G \, dt - \int_0^{T_{cycle}} P_{EM} \, dt - \int_0^{T_{cycle}} P_{own} \, dt, \text{ Wh} \]

The minimum duration of the ICE on-state is 5 s. While avoiding cases of storage charge of more than 100%, the ICE is switched off without considering time delay, as well as energy recovery to the ballast resistor. Display “% OnICE” shows the value of ICE working timeshare from the total cycle time.

Subsystem "S4". In the subsystem “S5” (Figure 9), the calculation of consumed fuel per cycle is carried out. The ICE’s on-off state diagram is connected to fuel consumption graph input. After that, it is converted to liters and displays the value reduced to 100 km.

Figure 6 – Subsystem “S2”.

Figure 7 – Subsystem “S3”.

Figure 8 – Subsystem “S4”.

Figure 9 – Subsystem “S5”.
The share of ICE on-state was 29%, fuel consumption was 5.78 l/100km. For buses with commensurate maximum weight, considering traffic in Siberia, in a city with the population of 1 to 3 million people, the fuel consumption rate was equal to 14 l/100 km [9]. Thus, the hybrid power source allows reducing fuel consumption by more than 2 times. State of charge diagram is shown in figure 10.

5. Conclusion
The basic equations for getting optimal parameters of the series hybrid power source with buffer ESU are obtained. The dependence of the required energy intensity of the buffer ESU on the PES power based on energy consumption of the vehicle according to standardized driving cycle WLTC is obtained. Apart from that, the zone with power source optimal parameters is represented on the dependence.

A Gazelle City car model was chosen as the object of simulation when driving according to WLTC. As a result of the simulation, the theoretical data were verified and refined. It has been found that the share of ICE on-state was 29%, while the fuel consumption was equal to 5.78 l/100 km. Therefore, using of the series configuration of the hybrid with buffer ESU will reduce ICE required power by 2 or more times, while reducing fuel consumption by more than 2 times with maintaining the range and driving dynamics.

References
[1] Grushevenko E 2019 Electric cars in Russia: risks and opportunities Retrieved from: https://www.eprussia.ru/epr/379-380/6557568.htm (in Russian)
[2] Malishev O, Sinizhkina V, Smishenko-Mironova A 2019 Overview of Russian automotive market in the 1st half of 2019 and development prospects Retrieved from: https://www.pwc.ru/ru/materials/pwc-auto-press-briefing-2019.pdf (in Russian)
[3] Wang C Zhang G Ge S Xu T Ji Y Yang X Leng Y 2016 Lithium-ion battery structure that self-heats at low temperatures Nature 529 pp 515–518
[4] Buligina O N, Korshunova N N, Kleshenko L K, Arzhanova N M, Dement’eva T M 2016 Weather in the Russian Federation in 2016 Retrieved from: http://meteo.ru/pogoda-i-klimat/93-klimaticheskie-usloviya/697-%09%09pogoda-na-territorii-rossijskoj-federatsii-v-2016-godu (in Russian)

[5] Dedov S I 2017 Study of a hybrid power source for electric vehicle applications Integraciya sovremenny’x nauchny’x issledovanij v razvitie pp 234-236 (in Russian)

[6] Kluchev V I 1985 Teoriya e’lektroprivoda [Electric drive theory] (Energoatomizdat) p 560

[7] GAZ Gazelle |City technical specifications Retrieved from: https://www.drom.ru/catalog/gaz/gazelle_city/274782/

[8] Myatezh A V, Yaroslavtsev M V, Zabelina D D 2014 The study of seasonal changes in the electric energy consumption of trolleybuses Nauchnye problemy transporta sibiri i dalnego vostoka 1-2 pp. 282-286

[9] Ministry of Transport of the Russian Federation 2014 Flow rate of fuel and lubricant materials by transport Retrieved from: https://mvf.klerk.ru/spr/spr87.htm

[10] Yaroslavtsev M V, Shtang A A, Dedov S I, Wu X 2018 Calculation of hybrid bus power demands by standard driving cycles The 19 international conference of young specialists on micro/nanotechnologies and electron devices (EDM) pp 469-472