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The reduction of auxiliaries power demand: The challenge for electromobility in public transportation

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ABSTRACT

An important role in the consumption of electric energy in urban transport are non-traction needs (auxiliaries), the main part of which is heating and air condition (HVAC). Auxiliaries are responsible for almost half of total energy consumption (normal weather conditions) and in the winter (or hot summer) it reaches up to 70% in daily scale. The reduction of energy used for non-traction needs is currently the main challenge related to the reduction of energy demand of means of transport. It is particularly important for battery vehicles, powered from an energy source with a very limited capacity.

The article presents the analysis of the influence of air temperature on the energy consumption of electric traction carried out on the basis of the real data measurement analysis. The relation between the ambient temperature and the demand for heating power was determined quantitatively. The impact of traffic delays on auxiliaries energy consumption was analyzed and it was shown, that traffic congestion can result in 60% overall energy consumption increase. Presented researches also refer to the relationship between the bus charging cycle (night charging, opportunity fast charging) and the optimal value of energy consumption, which should be assumed for energy calculations. Depending on the charging mode, the differences can reach up to 50%.

In the final part of the article, different methods of optimization of non-traction needs systems were compared.

1. Introduction

Sustainable energy was defined as energy sources that should be depleted within a time frame appropriate for the human race. Transport plays a very important role in sustainable energy consumption (Olabi, 2014). The development of non emission public transportation modes is one of the strategic EU policies. Urban transport is currently responsible for 40% (Falvo et al., 2011) of the total CO2 generated by road traffic in Europe. The transportation accounts for 30% of the overall energy consumption and 27% of greenhouse gas emissions. Of all the sectors that emit CO2, the transport sector is one of the fastest growing sector (Wang et al., 2007). As indicated in the European Commission's last white paper, all these factors can lead to an increase in mobility in the range of 24%–38% for the transport of goods (Usón et al., 2011). However, by 2050 emissions caused by transportation needs to be reduced by 60%, Achieving this will be a great challenge. What is more, the instability of fuel prices has a significant impact on the economy (Kühne, 2010). It become important to reduce energy consumption of transport sector and increase the use of renewable sources (Scarpellini et al., 2013). However, energy conversion in transport systems is complex process. It involves many levels of processing during which losses are generated (Bartłomiejczyk and Połom, 2017). Electricity seems to be a natural alternative to liquid fuels. For this reason, EU is actively supporting the development of electric transport, as evidenced by co-financing initiatives promoting environmentally friendly urban transport systems (Table 1).

The introduction of electric vehicles is one of the methods to create sustainable transport. This involves, among others with increasing their energy efficiency. In recent years a significant increase in the efficiency of electric drive systems has been observed. These findings resulted in a decrease in energy consumption for traction purposes in electric vehicles, e.g. overall annual energy consumption of trolleybuses in Gdynia reduced from 2.7 kWh/km

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Nomenclature list

Q'	heat flow [J/s]
d	thickness of the partition [m]
S	the cross-sectional area (m^2) perpendicular to the path of heat flow
λ	the thermal conductivity (W/(K·m)) of the partition
T	time
ΔT	temperature drop
P_h	heating power [kW]
v_{av}	commercial speed [km/h]
e	energy consumption per distance [kWh/km]
E_{tot}	total energy consumed by vehicles during day including consumption during technical breaks [kWh]
E_{tot_op}	energy consumed by vehicles during operation during day [kWh]
E_{tr}	energy consumed for traction needs by vehicles during day [kWh]
l_{day}	total transportation work (distance) by day [km]
D	delay of arrival
t_r	time
t_r	real arrival time
t_{sch}	schedule arrival time
P	energy consumption [kW]
Δt	period of averaging [h]
t_0	start time of averaging
$l_{\Delta t}$	distance traveled in period Δt [km]
E_{bat}	battery capacity [kWh]
l	travel distance [km]
$l_{\Delta t}$	analyzed distance [km]
v	actual speed [km/h]
k	the minimal level of battery charge
$P_t(t)$	probability of this delay t
$P_T(T)$	the probability of occurrence of temperature T

Table 1
EU project focused on urban transportation and reducing of energy demand of public transportation.

Project name	Duration	Scope of the project	Literature
Trolley	2010−2013	Promoting trolleybuses and developing energy-saving technologies in these vehicles	(Trolley)
Actuate	2012−2015	Accentuate the importance of driving technique for the energy efficiency of electrically-powered transport modes, implementation of the ecodriving concept	(Actuate)
Civitas Dyn@mo	2013−2015	Developing modern and energy-efficient technologies in urban transport	(Dyn@mo)
Osiris	2012−2015	Optimals strategy to innovate and reduce energy consumption in urban rail systems	(Osiris)
EBSF 2	2015–2018	Reduction of energy consumption in electric buses (e.g. reduction of non-traction consumption, use of Ecodriving)	(EBSF)
Trolley 2.0	2018–2020	Developing of trolleybus transport system	(Trolley 2.0)
EfficienCE	2019–2022	Energy efficiency for public transportation in Europe	(EfficienCE)

in 2005 year to 2 kWh/km in 2012 year (Bartłomiejczyk and Połom, 2016). The development of propulsion technology of traction drives, the introduction of energy-saving methods of speed regulation based on high efficiency power converters with 90–97% efficiency (Bartłomiejczyk et al., 2017), the increase of braking energy recovery resulted in a 20–30% reduction in energy consumption for traction purposes (Hrbac et al., 2014). Modern technologies of Smart Grid energy systems are also being popular (Bartłomiejczyk, 2018b).

On the other hand, passengers' expectations related to standards of travel comfort rise, which contributes to the increase in the power of heating devices and air condition. Besides, the number of additional board systems, such as passenger information systems, ticket vending machines and USB chargers is growing. The result of these two factors is the increase in the relative share of energy consumption for heating purposes in the electric transportation in relation to the total energy consumption and hence the more significant impact of weather conditions on the energy consumption in electrified transport.

An important feature of electric vehicles is the limited possibility of providing energy for heating the vehicle and the lack of the possibility of using waste energy for this purpose. The low efficiency of internal combustion machines makes it possible to heat the interior of buses and other vehicles fueled by liquid fuels and gas by cooling energy of the engine. In contrast to that, electric drive systems are characterized by high energy efficiency, which in the current development of technology reaches 90–95%. This means that the interior heating of the vehicle is possible only with the help of electricity drawn from the traction network.

In the conflict with the changes in the nature of the traction network load, there is an increase in expectations regarding the forecasting of electricity consumption. Currently, the number of transportation companies purchasing electricity on the open market is growing. It is to be expected that in the nearest future these enterprises will also start to purchase energy on the stock exchanges and to schedule and balance energy consumption on their own. Then the key issue will be the precise prediction of electricity consumption. Such a situation will first of all require the use of tools predicting energy demand based on the expected weather conditions.

The second area where the issue of heating energy demand is the key issue are electric vehicles with autonomous supply. In contrast to vehicles supplied from the traction supply network (overhead catenary line or the third rail), they are powered by traction batteries. Therefore, it is very important to carefully analyze the energy distribution and reduce energy consumption, primarily for heating purposes. The price of traction batteries can reach for up to 50% of the price of an electric vehicle. Energy usage for heating purposes can reach for over 50% of total energy consumption, which requires significant oversizing of the battery. For this reason, the issue of energy demand of non-traction purposes is a fundamental problem in the optimization of electric vehicles and minimization of costs.

Literature lists energy consumption values that fall within a very wide range. For example, in (He X. et al., 2018) average energy consumption are estimated to be 1.7 to 4.1 kWh/km. A numerical simulation model based on surrogate model is applied in (Vepsäläinen et al., 2019). The energy demand of the surrogate model varied from 0.43 to 2.30 kWh/km, which indicates a very large dispersion, but these were only simulation and theoretical studies. It should be emphasized that the temperature was indicated as the main factor affecting energy consumption.

In energy analyzes, simplified models of non-traction loads are usually used, based on a constant power value. In (Lajunen, 2018) is proposed a simplified model to estimate electric bus energy consumption in different weather conditions using measured data from existing bus lines. The required auxiliary power was assumed to be 6 kW in mild weather conditions, 14 kW in cold or hot conditions, and 22 kW in extreme cold conditions. In many analyzes, the power required for electric heating is omitted and heating with diesel or oil is assumed. In (Correa et al., 2017), the vehicle longitudinal dynamics model was used to calculate the required power for electric bus. The auxiliary power for air conditioning systems, pumps, lights, and instruments assumed to be constant at level of 6 kW but without electrical heating. Analogically, authors in (He He et al., 2018a,b) proposed a predictive air-conditioner control for electric bus with passenger amount variation forecast, but without heating. Similarly, in (Gallet et al., 2018) the constant power of non-traction loads was assumed and the data was analyzed and only the heating work was limited. An interesting solution of direct recovery of braking energy to heat is presented in (Ye et al., 2019). The problem of optimizing non-traction needs is addressed in publications on dynamic charging of electric buses (Suh et al., 2015). Another example of the importance of the issue of energy consumption for heating purposes is a study which presents the optimization of door opening in the metro system (Hu and Lee, 2004).

The main objective of the article is to fill the gaps in the current literature and present the analysis of energy consumption for non-traction needs of electrical buses based on measurements carried out in the transport system. The specific objectives are to show the nature of the variability of energy consumption, qualitative and quantitative estimation of the impact of traffic congestion and determining the time characteristics of the load. These results will optimize the work of non-traction systems and optimize battery capacity.

The article will present three aspects of supplying auxiliaries in electric buses:

- influence of outside temperature on energy demand of auxiliaries
- influence of traffic congestion on energy demand of auxiliaries
- statistical aspects of energy demand of auxiliaries.

All presented analysis are based on the measurements realized in Gdynia's trolleybus system.

The power supply is the feature which differs trolleybus from the electric bus. In the standard trolleybus, the power source is electricity from the overhead contact line, while the stationary charged electric battery bus is powered by traction batteries. This difference has a major impact on the supply system and electrical equipment of the vehicle. However, from the energy consumption perspective both types of vehicles are very similar. Trolleybuses and electric buses have the same mechanical construction. Traffic conditions and the influence of congestion are also the same. Moreover there are many transitional solutions between standard trolleybuses and stationary charged battery buses. The battery hybrid trolleybuses and dynamic charged electric buses are an example of those solutions. Trolleybuses are the tool which has brought a huge source of experience to the development of the electric transport (Borowik and Cywiński, 2016). This experience can be applied to all other types of electric buses (Bartlomiejczyk, 2019).

Trolleybuses in Gdynia are equipped with the energy data logger system, which records every second main electrical and mechanical parameters of the ride. The recorded parameters include the values of speed, traction drive current, vehicle current, and GPS location. This has resulted in a huge database of trolleybuses' energy consumption. The collected data provides opportunities for detailed analyses. From the point of view of mobility characteristic, trolleybuses are very similar to electric buses. Due to this fact, the Gdynia trolleybus network can be a perfect test ground for analyzing e-mobility and energy efficiency of e-vehicles (Bartlomiejczyk, 2019). Whenever it is mentioned in the article about specific measurement tests, they will be based on data from the Gdynia trolleybus system and the name of the trolleybus will be used. However, the conclusions drawn will apply to all electric buses and then we will use the name "electric bus".

2. Energy consumption for auxiliaries

2.1. *Auxiliary system in electric bus*

The auxiliary systems comprise the electrical equipment of the vehicle which is not directly used in the generation of traction force. The following elements can be included in auxiliary systems:

- compressor and hydraulic pump motors
- supply of low voltage equipment
- air conditioning
- heating

In the Table 2 the main auxiliaries systems in standard electric bus are compared.

The lightning, passenger information systems, charging of DC batteries and air compressor are responsible for 20–25% of total energy consumption. In practice, the last two elements form the main part of the auxiliary load, with heating in particular, are the mains factors.

2.2. *Thermal energy flow of electric bus*

The source of thermal energy in the vehicle are the heating system and, partly, passengers. The heat is excreted outside to the environment in the process of thermal conduction through the walls of the vehicle and the exchange of heat through doors, windows and ventilation system (Bartłomiejczyk and Połom, 2013). Based on the heat flow equations and Fourier's Law for heat conduction, a given heat flow Q' transferred by partition in the steady state and with a small temperature drop ΔT can be described by the dependence:

Table 2
The range of nominal power of the main auxiliaries systems in 12 m electric bus or trolleybus.

System	Nominal power
Lightning	1–2 kW
Passenger information systems, ticket vending machine	1–3 kW
Charging of 24 V board batteries	0,5 - 2 kW
Air compressor	3–6 kW
Hydraulic pump	2–4 kW
Air condition	10–16 kW
Heating	5–25 kW

$$Q' = \lambda \frac{S \cdot T}{d} \tag{1}$$

The power used for heating the vehicle is equal to the amount of thermal energy transferred outside the vehicle. Assuming that the heat dissipation takes place only by transferring heat energy through the side surfaces, roof and chassis, after converting dependence (1), the heating power necessary to maintain a constant temperature inside the vehicle is equal to the heat flow from the vehicle:

$$P_h(T) = \frac{Q'(T)}{1000} \tag{2}$$

The linear nature of the dependence (2) is confirmed by the scatter of scatter graph of non-traction needs as a function of the temperature difference inside - outside presented on the Fig. 4. Average energy consumption per 1 km on auxiliary purposes depends on the commercial speed v_{av} of the movement and can be described by formula:

$$e(T) = \frac{P(T)}{v_{av}} \tag{3}$$

Measurements of energy consumption were carried out in trolleybuses operated in Gdynia. For this purpose the energy consumption data - log recording system was used.

The Trolleybus Transportation Company in Gdynia (PKT) operates trolleybus network in Gdynia (Poland). Almost 90 vehicles with a standard length of 12 m are used.

Heating of trolleybuses is carried out using electric heaters supplied directly from the traction network by 600 V DC or by 400 AC through DC/AC inverter. In each trolleybus there are three types of heating devices whose parameters vary depending on the type of vehicle:

- passenger space heaters with a power of 10–20 kW
- 3 kW driver's cab heater
- windscreen heater ("frontbox") which power is regulated smoothly in the range of 0–20 kW.

The heating is controlled manually, the driver's task is to prevent the temperature inside the vehicle from falling below 16 °C. Interior heaters and driver cabins are equipped with thermostats that prevent overheating of the heating coils.

3. Calculations and results

3.1. Overall analysis of energy consumption

The power source of the electric vehicle may be a traction network, an autonomous energy generator (eg a diesel unit, a hydrogen fuel cell) or a traction battery. Energy collected from the power source is intended for:

- vehicle driving needs
- traction needs,
- non-traction needs.

Energy collected for non-traction purposes can be divided into:

- supply of non-traction needs during movement
- supply of non-traction needs during stops.

The first component concerns the energy consumption during operation with passengers on the route. This is the actual energy used to keep passenger comfort. The second parameter applies to energy consumption during technical stops (at terminuses, breaks for drivers) and has only an indirect effect on comfort. For this reason, it can be optimized in a relatively easy way. The distribution of electric energy consumed by vehicles is shown on Fig. 1. To emphasize the importance of energy consumption for non-traction needs, Fig. 2 shows the percentage distribution of energy consumption in annual scales for whole trolleybus system. The values were set on basis on measurements from vehicle data loggers systems is based on total energy consumption in a year. It shows that energy consumption for non-traction needs (HVAC) has a significant impact on the total energy consumption in the transport system.

A key parameter affecting the energy consumption is the external temperature. The collected measurement data allowed for a quantitative assessment of this dependence (Bartłomiejczyk, 2018a). Fig. 3 presents the average total energy consumption per km of a trolleybus as a function of the temperature difference inside versus outside. The scatter graphs illustrate the value of non-traction energy consumption per distance (Fig. 4) as a function of the temperature difference inside. As in the case of the previous analysis, the values were set on basis on measurements from vehicle data loggers systems. Measurements from all trolleybus lines from November to April were used for the analysis. 5600 of data points was taken into analysis. The points shown in the graphs indicate energy consumption during a single journey of trolleybus - one dot means one journey. For temperature drop ΔT bigger than 5 C° the values of non-traction needs $P(\Delta T)$ and energy consumption per distance of non traction needs $e(\Delta T)$ can be approximated by linear functions:

$$P(T) = 0.91 \cdot T + 0.44 \tag{4}$$

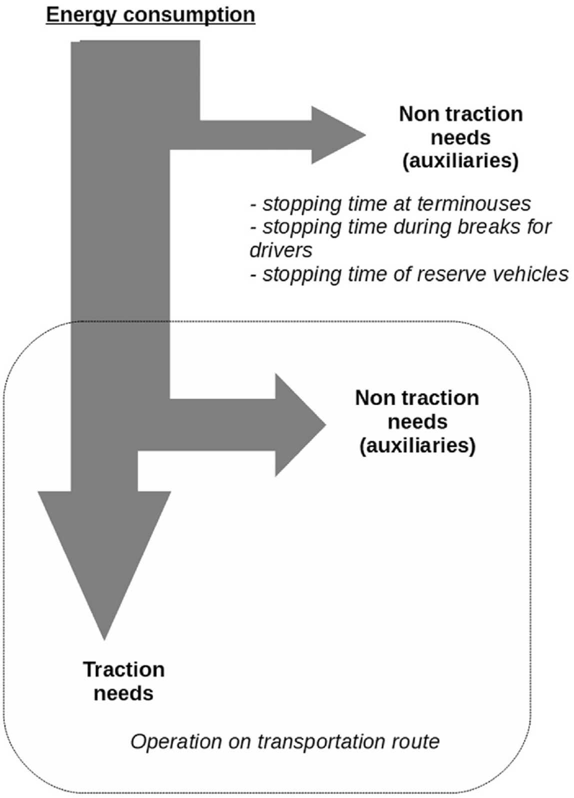

Fig. 1. The distribution of electric energy consumed by vehicles.

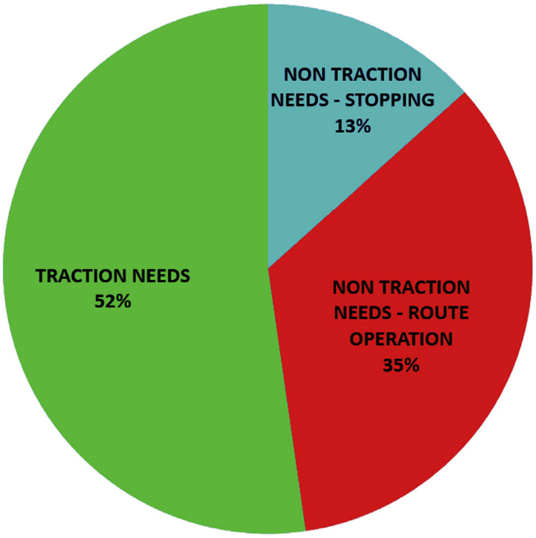

Fig. 2. The overall annual structure of energy consumption.

$$e(T) = 0.052 \cdot T + 0.022 \tag{5}$$

Under standard operating conditions, the non-traction energy consumption is up to 1.2 kWh/km, which accounts for a total energy demand of around 2.5 kWh/km. It may be even higher in case of disturbances caused by congestion, which results in a decrease in commercial speed of the vehicle. The effect of this may be an increase of energy usage for non-traction purposes according to the formula (3). It explains high values of average energy consumption on non-traction needs of several measurements shown in Fig. 4, which exceeds 1.6 kWh/km. This requires a significant increase in battery capacity. On the other hand, periods of significant demand occur very rarely (less than 1% of registered journeys). For this reason, it is recommended to use heating power control. If the battery is discharged under a certain level heating power must be reduced. For example, a reduction of the inside temperature of the vehicle by 8 °C reduces the energy consumption by 0.5 kWh/km. This solution can be used in the event of non-standard traffic situations and avoids excessive energy usage.

The share of non-traction needs in total energy consumption (Figs. 2, 5 and 6) is presented on an annual basis. The following average energy consumption indicator in one-day scale values will be defined:

- overall average energy consumption referred to all amount of consumed energy:

$$e_{tot} = \frac{E_{tot}}{l_{day}} \tag{6}$$

- average energy consumption referred to consumed energy during operating time:

$$e_{tot\_op} = \frac{E_{tot\_op}}{l_{day}} \tag{7}$$

- average energy consumption for traction needs:

$$e_{tr} = \frac{E_{tr}}{l_{day}} \tag{8}$$

The values of energy consumption indicators and daily average outside temperature in annual scale are shown on Fig. 5. The relationship between outside temperature and energy consumption for non-traction purposes is very visible. The fall in outside temperature in November—March causes a significant increase in energy consumption. There is also a noticeable lack of a visible relationship between outside temperature and energy consumption for traction needs. Fig. 6 presents the value of all energy consumption for non traction needs referred to overall energy consumption (participation of auxiliaries in overall energy consumption).

It should be noted that on an annual basis, non-traction needs consume nearly half of the total energy consumed by vehicles. When the outside temperatures are very low or very high, consumption for non-traction purposes, heating or cooling can reach a value close to 70% of total consumption.

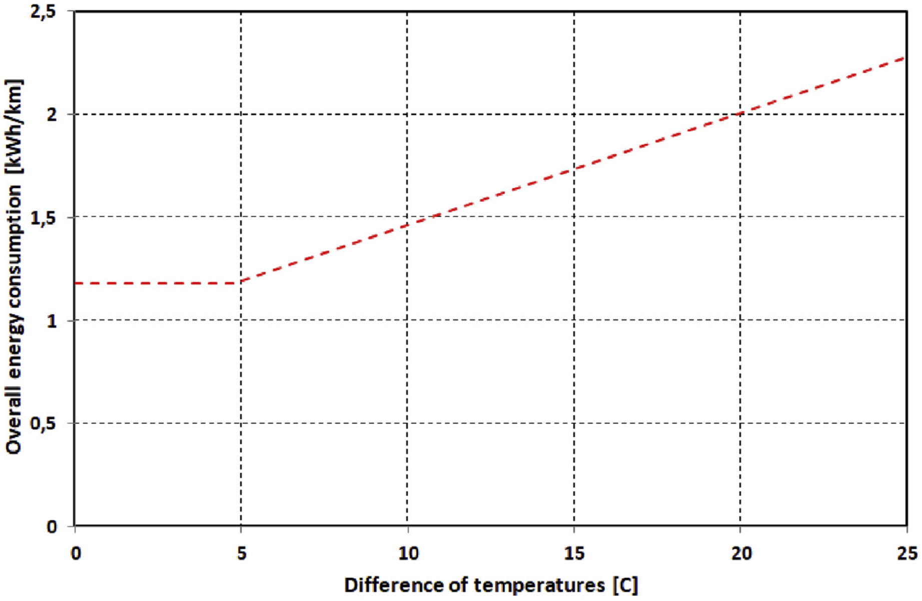

Fig. 3. Overall vehicle power consumption in function of difference between ambient and internal temperature ($R^2 = 0{,}6494$).

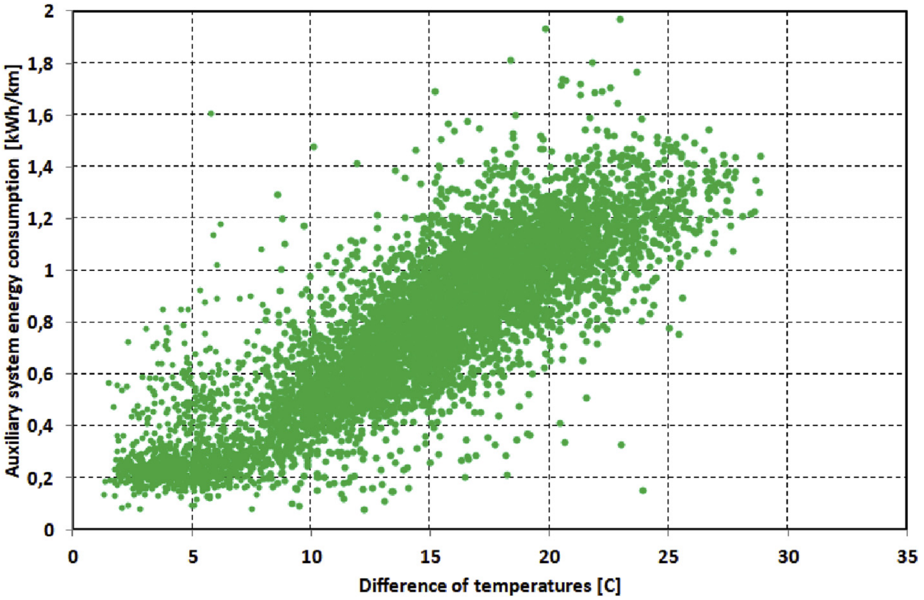

Fig. 4. Scatter chart of auxiliary energy consumption per distance in function of difference between ambient and internal temperature.

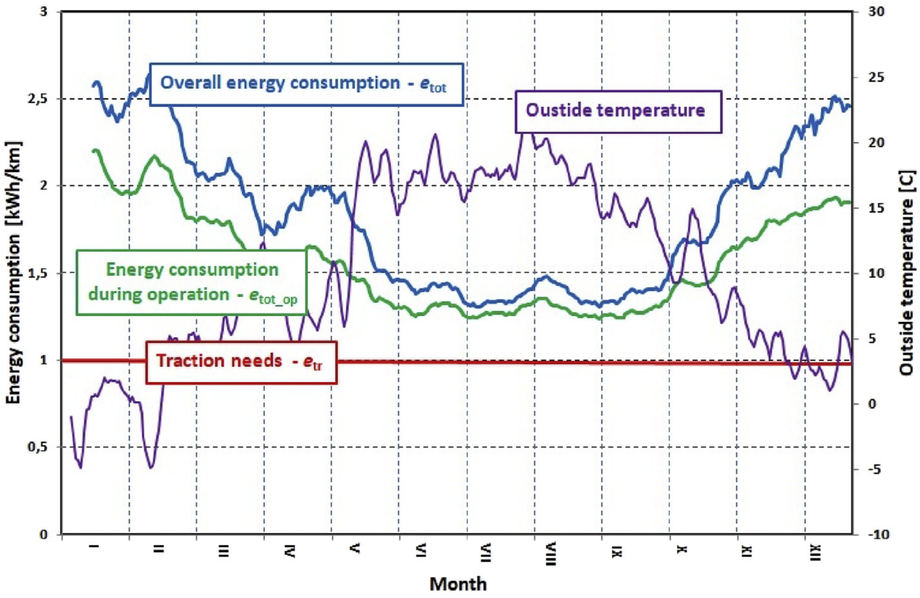

Fig. 5. The values of average energy consumption and daily average outside temperature in annual scale.

3.2. Influence of traffic congestion on energy demand of auxiliaries

Congestion of road traffic affects both: energy consumption for traction as well as non-traction purposes (auxiliaries). The energy consumption for driving (traction needs) is mainly dependent on the maximum value of speed. Hence, an increase in the speed of traffic may increase the demand for energy. However, other factors need to be taken under consideration as well, as the problem is complex (Bartlomiejczyk, 2019). In the case of energy demand for non-traction purposes, traffic congestion has decidedly negative impact: reducing the speed of movement increases the time of travel, which results in the increase of energy usage. The influence of traffic congestion on the consumption of auxiliary needs was shown in experimental way by:

- analysis of dependence between commercial speed and energy consumption,
- analysis of dependence between timetable adherence and energy consumption.

In order to present experimentally the influence of speed on energy consumption, the section of trolleybuses route between stops “Dworzec Główny PKP” and “Morska Estakada” on Morska street, with the length 2,5 km, was analyzed. This section is characterized by the occurrence of significant congestion of road traffic during rush hour, which allows the study of the impact of traffic disruptions on energy consumption in a wide range. In addition, it is one of the main sections (with the highest traffic intensity) of the Gdynia trolleybus network. The analysis of energy consumption for

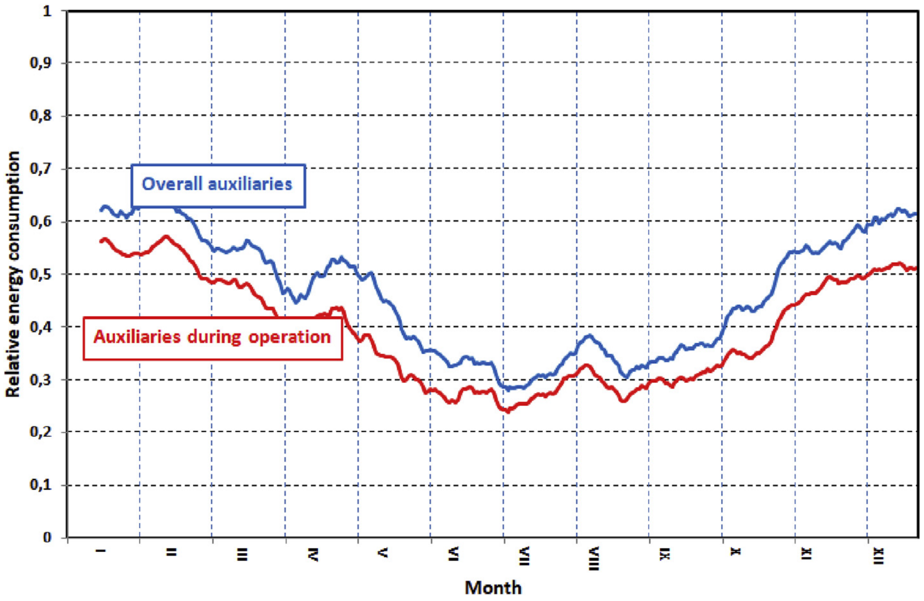

Fig. 6. The value of all energy consumption for non traction needs referred to overall energy consumption in annual scale.

traction, non-traction needs and overall energy consumption was carried out. The two analyses were provided:

- analysis based on registration from data logger systems of vehicles, which allowed to show the influence of commercial speed,
- analysis based on Tristar system, which allowed to show the influence of timetable adherence.

3.2.1. *Influence of commercial speed*

The analysis was made out during the spring and winter periods. The scatter plot of energy consumption in function of speed are shown on Fig. 7 (winter season: December—February) and Fig. 8 (spring season: May—June).

Tables 3 and 4 presents indicators of dependence between energy consumption and commercial speed, obtained from the linear regression model. A relative large value of linear regression coefficient (−0,0481 in winter versus −0,0188 in spring) and R^2 coefficient (0,4166 in winter versus 0,1052 in spring) of non-traction consumption in winter season is noticeable. They confirm the strong impact of commercial speed on energy consumption for non-traction purposes in the winter season.

3.2.2. *Influence of timetable adherence — Tristar system*

The Tri-City (Gdańsk, Sopot, Gdynia) Intelligent Agglomeration Transport System (Tristar) is designed to automatically control traffic in the Tri-City area (Trolley Project). Work on it has been ongoing since 2006. It was launched on December 10, 2015. It uses technologies in the field of Intelligent Transport Systems (ITS).

The system includes devices such as:

- CCTV that help register drivers breaking the law - overspeeding or passing through the red light,
- sensors on parkings that detect if the spot is taken or not,
- tables and variable-message signs (VMS) to inform drivers about weather and road conditions,
- passenger information systems (PIS).

The Tristar system carries out many measurements regarding vehicle traffic in the Tri-City road network. One of the measured values is the time of arrival and departure time of buses and trolleybuses from stops. It is compared to the theoretical time of the timetable. In this way delays in the public transport traffic are measured. The delay amount was calculated as a relative difference:

$$D = (t_r - t_{sch})/t_{sch} \tag{9}$$

A positive value of the *D* indicator means that the actual travel time was longer than the timetable (delay). A negative delay value indicates that a given connection is faster than planned time.

The data from the Tristar system from October 2017 was used for the analysis. These include trolleybus routes of line 29 (Grabówek SKM - Wielki Kack Fikakowo) and line 710 (Wielki Kack Fikakowo - Grabówek SKM).

In order to identify the hours in which the travel delays are bigger, data from weekdays from the first week of the month were analyzed - from Monday, October 2, 2017 to Friday, October 6, 2017. A total number of 71 courses were taken into account. The biggest delays occurred around 10:25 (7.8%) and 15:22 (14.2%). At these times of the day, the probability of congestion on the analyzed section turns out to be the greatest. On the other hand, the slightest delay occurred at 08:43 (−0.6%) and 12:24 (−0.9%) hours.

Next step consists of studying how the delay value affects the energy usage. Energy consumption in function of delay is shown in Fig. 9.

Both the analysis of the impact of speed on energy consumption and the analysis of the impact of traffic delays showed an increase in overall energy consumption with an increase in traffic congestion. Although the reduction of the commercial speed causes a slight decrease in energy consumption for traction purposes, at the same time there is a much higher increase in the demand for auxiliaries. What is more, this impact is visible much greater in winter than in spring. Therefore, it can be concluded that the decrease in the speed of motion causes an increase in total energy consumption.

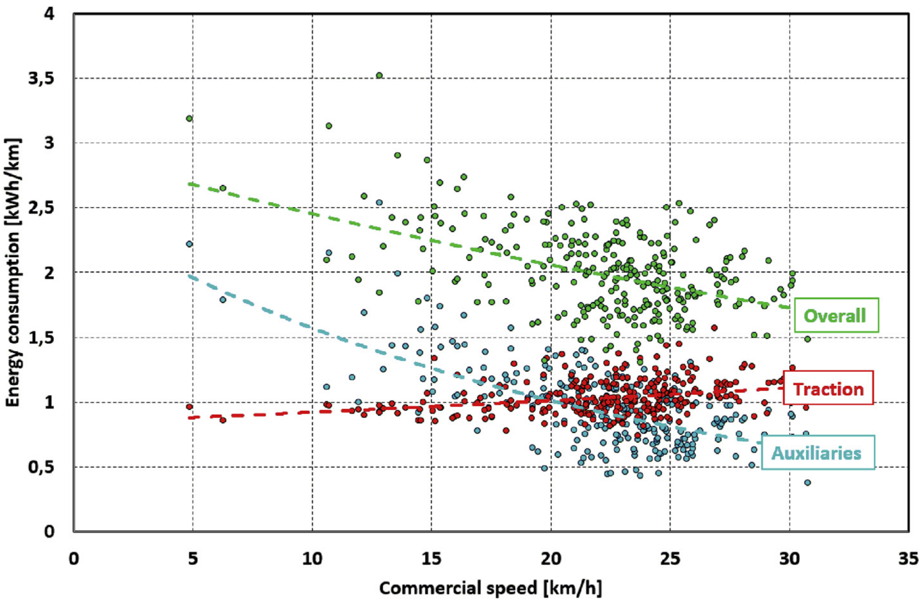

Fig. 7. Scatter plot of measured average energy consumption in function of commercial speed for winter season (discontinuous lines means trend lines).

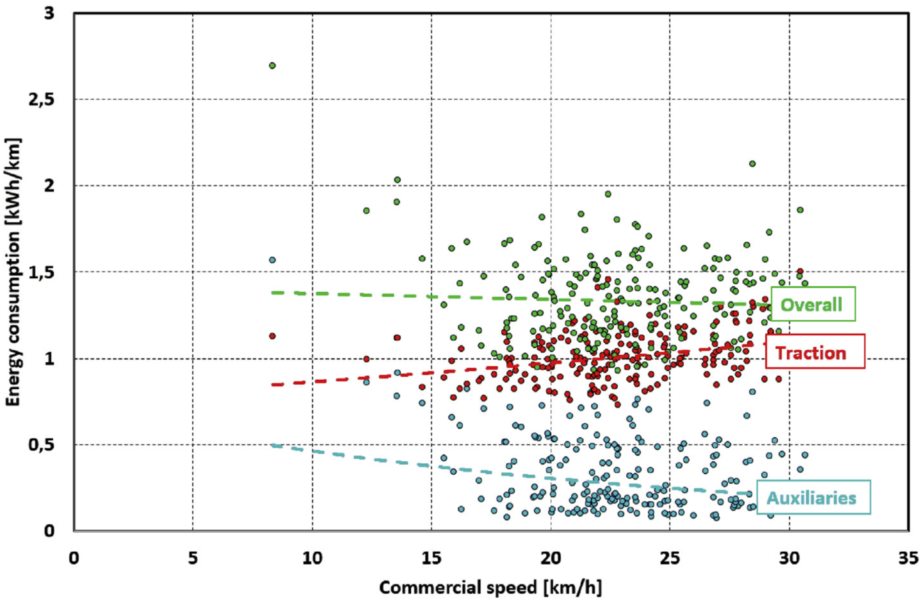

Fig. 8. Scatter plot of measured average energy consumption in function of commercial speed for spring season (discontinuous lines means trend lines).

Table 3
The values of the linear regression coefficient for the measurements shown in Figs. 7 and 8.

	Winter	Spring
Traction	0,0097	0,0125
Auxiliaries	−0,0481	−0,0188
Overall	−0,0384	−0,063

Table 4
The values of the R^2 coefficient for the measurements shown in Figs. 7 and 8.

	Winter	Spring
Traction	0,0919	0,1085
Auxiliaries	0,4166	0,1052
Overall	0,24	0,029

3.3. *Time characteristics of energy consumption*

The average energy consumption per distance *e* can be defined as:

$$e(t_0,\ l_{\Delta t}) = \frac{\int_{t_0}^{\Delta t + t_0} P(t)dt}{l_{\Delta t}} \tag{10}$$

where t_0 means start time of averaging. From point of view of battery capacitance and operation on the route the distance plays the main role, so the analyzed distance (averaging distance) $l_{\Delta t}$ can be defined:

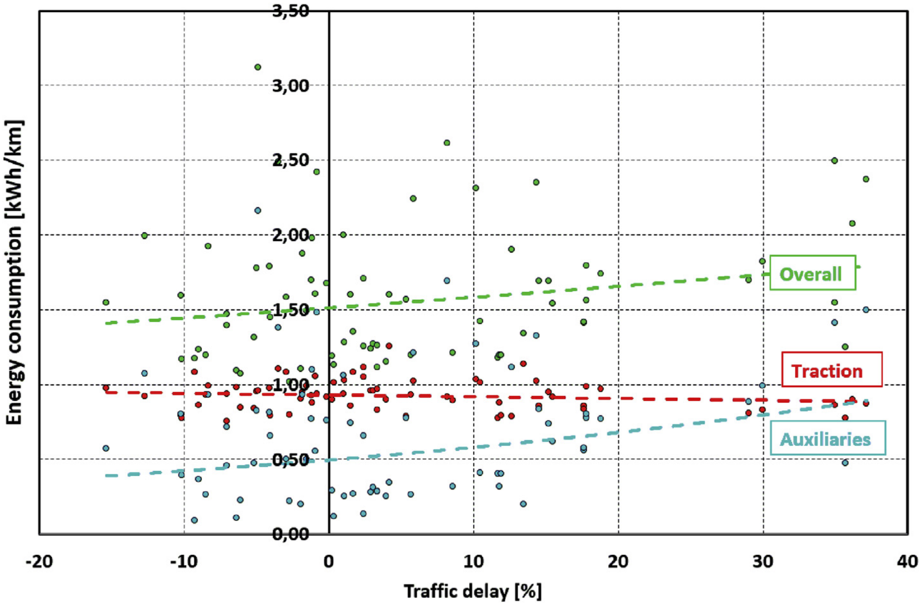

Fig. 9. Scatter plot of measured average energy consumption in function of traffic delay D for summer season.

$$l_{\Delta t} = \int_0^{\Delta t} v(t)dt \tag{11}$$

and for above mentioned reason it is important to analyze the variability of average energy consumption e in the function of distance $l_{\Delta t}$. Consequently, we can define an algorithm for determining the maximum energy consumption $e_{\max}$ in function of analyzed running distance $l_{\Delta t}$:

$$e_{\max}(l_{\Delta t}) = \max_{t_0=0:t_{\max}} e(t_0,\ l_{\Delta t}) \tag{12}$$

Determining the maximum energy consumption as a function of distance $l_{\Delta t}$ consists in analyzing the registrations of energy consumption in order to find the maximum of its average value for a given distance $l_{\Delta t}$ according (12).

Setting of period Δt and consequently analyzed distance $l_{\Delta t}$ plays an important role in estimation of the average value (Bartłomiejczyk, 2018a). Due to the random nature of vehicle traffic and the occurrence of traffic congestion, in particular during rush hours, the average value of energy consumption on a short-term scale, during peak hours (on the level of 1–2 h, corresponding to 10–20 km) may be higher than in a longer scale (full day, 150–200 km). This feature is presented on Fig. 10.

The dependence presented above affects the choosing of the traction battery capacity in the electric bus. In a simplified way, with a given travel distance l between charges, the battery capacity E_{bat} can be determined as:

$$E_{bat} = \frac{l \bullet e}{k} \tag{13a}$$

In case of opportunity charging systems, where batteries are charged at final stops, the distance l is at level 5–15 km. So the value of energy consumption must be assumed at the “higher” level, at 3–4 kWh/km. In overnight charging system the distance l is bigger (100–200 km), which allows to estimate the required battery capacity using lower value of energy consumption (2–2.5 kWh/km).

4. Example of case study

Benefits resulting from the use of heating power modulation will be shown on the basis of bus route 170 in Gdynia, which is designed for operation with electric buses in the In Motion Charging system. This investment will be implemented as part of the GEPARD project (Bartłomiejczyk, 2018c). Vehicles servicing this line on the section Węzeł Franciszki Cegielskiej - Węzeł Ofiar Grudnia ‘70 will use the existing trolleybus traction network and will be charged during movement (IMC). The remaining section of the Węzeł Ofiar Grudnia 70 - Pogórze Dolne, 5.5 km long, will be operated in battery mode. At the terminus Pogórze Dolne will be a charging station that will allow partial recharging of the battery when stopped. The section Węzeł Ofiar Grudnia 70 - Pogórze Dolne is characterized by significant traffic disturbances due to congestion, what significantly influences energy consumption. Fig. 11 shows the travel time histogram for this section. According to the schedule, it is 15 min, but in some cases it reaches 40 min. This is of great importance for energy consumption for non-traction needs, and hence for the required capacity of traction batteries.

Traffic congestion increases travel time. In the worst case (Fig. 11) the driving time with battery power is almost three times longer than the scheduled driving time. With constant power of non-traction needs, this may result in the need to significant increase the capacity of traction batteries. For this reason, an analysis of energy consumption will be carried out using the emergency reduction of heating power in the event of significant delays of traffic. The energy consumption and required capacity of the traction batteries will be compared for two variants:

(1) operation of auxiliaries with constant power while driving on battery power,
(2) operation of auxiliaries with constant power while driving on battery power for the scheduled driving time and switching off the heating in the event of a delay (exceeding the scheduled travel time).

Due to thermal inertia, turning off the heating system does not immediately cool the vehicle interior, what allows to keep inside

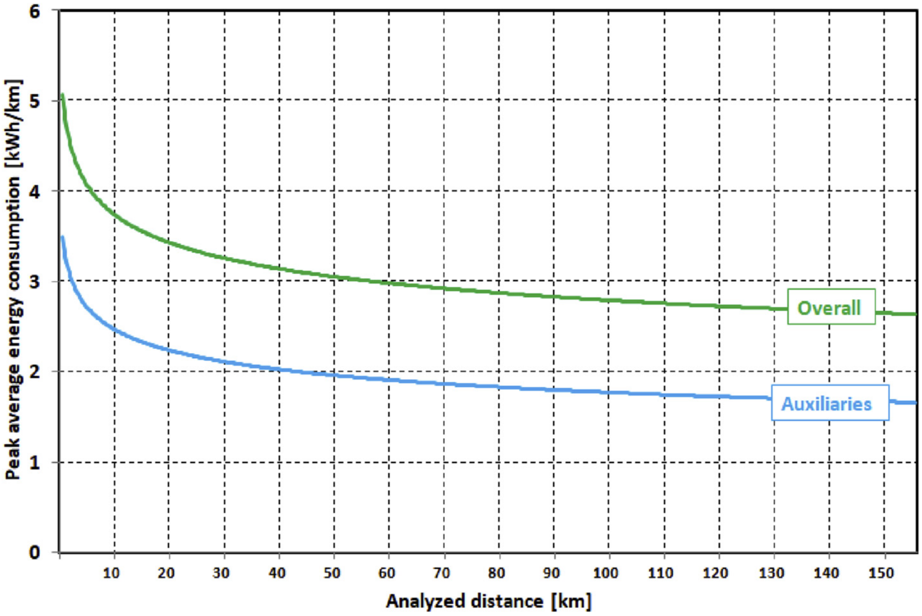

Fig. 10. The visualization of the maximal energy consumption in function of distance $l_{\Delta t}$.

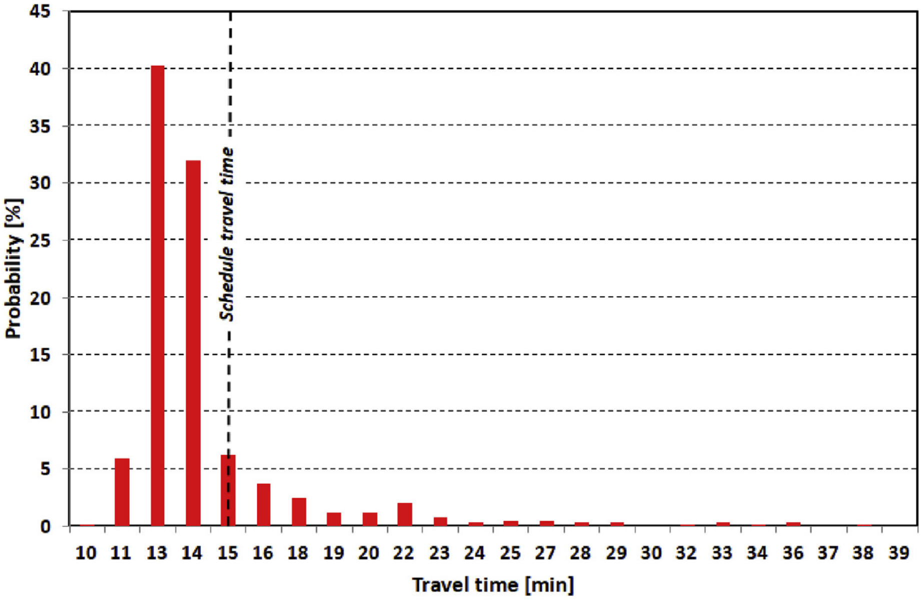

Fig. 11. The histogram of travel time of bus route 170 between stops Węzeł Ofiar Grudnia 70 and Pogórze Dolne.

temperature at relatively high level after switching off of the heaters. Thanks to this, limiting the vehicle's heating does not have to cause a significant reduction in passenger travel comfort. Therefore, in the second case, the analysis of the cooling process will be crucial. For this purpose, the trolleybus internal temperature recording of 7–8 January 2017, realized during test in winter weather, was used. At that time, the outside temperature was - 10 °C. The Fig. 12 shows the temperature course recorded during the technical test, in which the heating was turned off and the interior of the vehicle was automatically cooled during movement. The temperature change as a function of time can be approximated by the function:

$$T(t) = 25 \cdot e^{-0.0002 \cdot t} - 10 \tag{13b}$$

If the actual overall driving time t_{real} of the analyses section exceeds the scheduled driving time t_{sch}, the heating is switched off in the moment t_{sch}. A the final moment of the trip (reaching of the final stop), the interior temperature of the vehicle will drop to value T_{min}:

$$T_{min}(t) = 25 \cdot e^{-0.0002 \cdot (t_{real} - t_{sch})} - 10 \tag{14}$$

The purpose of this analysis is to determine the probability of occurrence of a specific value of the vehicle interior temperature, and then create a histogram of the temperature value. By transforming equation (13) it can be stated that the duration Δt of the temperature changes between values $T_{\mathrm{i-1}}$ and T_1 (the temperature drop) during cooling of the vehicle will be as follow:

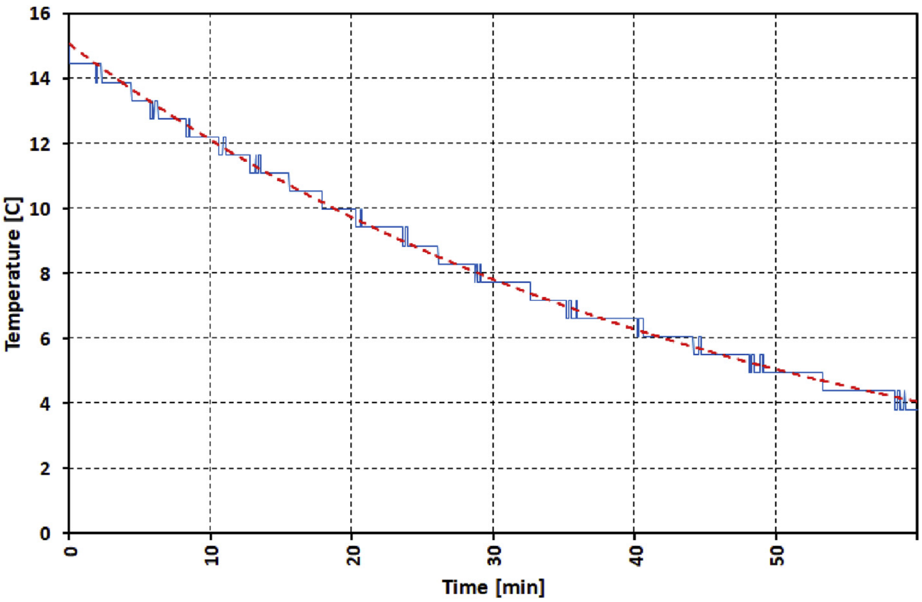

Fig. 12. The time characteristic of self-cooling of the trolleybus interior at an outside temperature of −10 °C (R^2 = 0,99).

$$\Delta t(T_i) = -5000 \cdot \ln((T_i + 10) / 25) + 5000 \cdot \ln((T_{i-1} + 10) / 25) \tag{15}$$

Assuming the discretization of temperature measurement (e.g. every 1 °C) it can be stated that the temperature with the T value will last for the time duration Δt. The next stage is determining the probability of occurrence of a given temperature T (with 1 °C discretion) of the vehicle interior during the service of the line with battery power supply of vehicles. For this purpose, the times of occurrence Δt of a given temperature T (15) for a course with a given delay P_t (t) by the probability of this delay (histogram presented in Fig. 11). After dividing by the total time the service of the line we get the probability of occurrence $P_T(T_i)$ of a given temperature T_i:

$$P_T(T_i) = \frac{\sum_{t=t_{\min}}^{t_{\max}} P_t(t) \cdot \Delta t(T_i)}{\sum_{T=T_{\min}}^{T_{\max}} P_T} \tag{16}$$

The results of calculation are shown on Fig. 13. Table 5 presents a comparison of the limiting values of energy consumption parameters in the case of vehicle heating with the use of power limitation after exceeding the scheduled driving time and without. Energy consumption for non-traction inches was determined using formula (4), while energy consumption for traction purposes was assumed at 1 kWh/km (Bartłomiejczyk and Połom, 2016), the distance of travel in battery mode is 5.5 km. Due to the required safety margin and extension of the battery life, their capacity is assumed assuming a minimum discharge level of 50%. A unit price of 1300 EUR/kWh was assumed for the battery price calculation (Bartłomiejczyk, 2018b).

The implementation of a reduction in heating power allows the required battery capacity to be reduced by 40%, which brings savings of 20 000. EUR per vehicle. On the other hand, for nearly 95% of the time, the temperature inside the vehicle will be in the required range (at least 15°), and in 99% the temperature will exceed 10°. Cases of significant cooling of the interior will be at the level of 0,5% of the service time of the line. Assuming a daily number of cycles on the analyzed transportation route at 100–200, it means excessive cooling of the vehicle only in one or two cycles. It should also be emphasized that days with low temperatures are relatively rare. Therefore, on a yearly basis, the reduction of passenger comfort will be minimal.

5. Discussion

The basic way to reduce energy consumption is to optimize the process of setting the value of temperature inside the vehicle. We should avoid overheating interiors and keeping the limit the maximum difference in temperature between the surroundings and inside of the vehicle (Beusen et al., 2013). Attention should be paid to the high share of energy consumption (13%) for non-traction purposes during technical stops (Fig. 6). For this reason, the power of heating and air-conditioning equipment should be limited during prolonged technical stops, when there are no passengers in the vehicle.

Another solution is active (intelligent) control of the power of non-traction devices in the vehicle, which is correlated with the operation of the vehicle drive system in order to increase the use of regenerative braking power to auxiliaries (Bartłomiejczyk and Połom, 2016). It consists in increasing the power of the receivers (in particular heating) during braking. As a result, energy recovered from braking is consumed in the place of its generation and transmission losses are additionally reduced (Laurikko, 2018).

The next step in reducing energy consumption may be the introduction of heat pumps. Thanks to the use of air conditioning devices made in modern technology (CO_2 heat pump), the energy consumption of the heating system can drop by 50–70% (Borealis, 2018). This means that the total energy consumption can be reduced by 20–50%. In addition, reducing of energy consumption brings with it the possibility of reducing the size of traction batteries in electric buses by 20–50%. The price of the battery is currently at the level of 700–1500 euros for 1 kWh and can be up to 50% of the vehicle price.

An important element related to the optimization of battery capacity is its selection depending on the real traffic requirements. For this reason, the time characteristic (Fig. 10) of energy demand by non-traction needs is important and should be taken in consideration during preparing of technical specification for vehicles. Also, a good solution which is recommended to use is

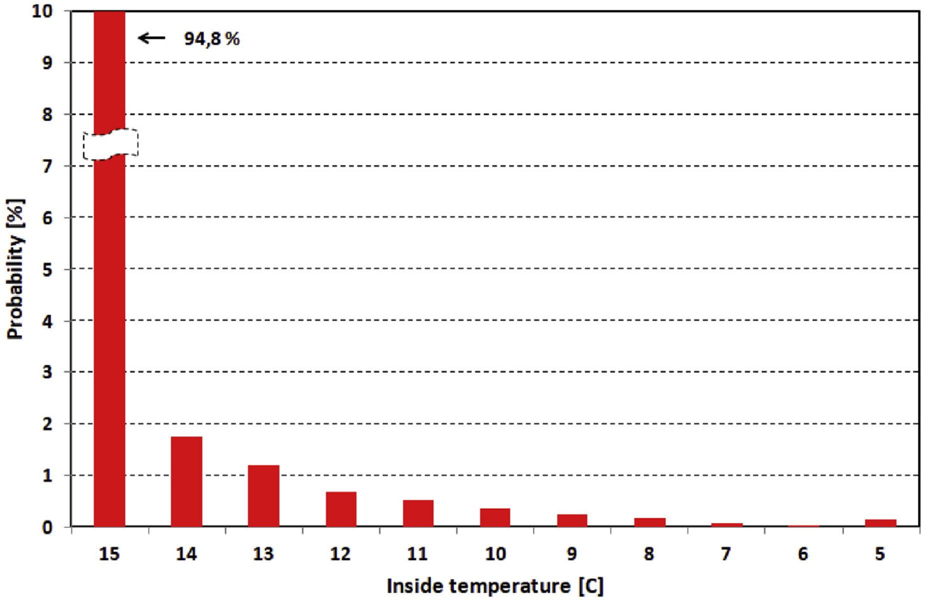

Fig. 13. The histogram of temperature inside vehicle during off wire mode of proposed changed line 170 with implemented reduction of heating power.

Table 5
Comparison of the requirement for traction battery.

	Energy consumption for auxiliaries [kWh]	Overall Energy consumption [kWh]	Required battery capacitance [kWh]	Price of batteries [k EUR]
Reduction	7,3	12,8	25,6	33
Standard	15,8	21,2	42,5	55

exceptional, emergency reduction of heating power in extreme situations (eg high traffic disturbances). This may cause a temporary discomfort for passengers, however, it allows to reduce the battery capacity and avoid excessive discharge. The situation of very high energy consumption (more than 3.5 kWh/h in case of standard vehicle) are very rare and require significant oversizing of batteries. For example, reducing the inside temperature in the vehicle by 5 °C in an emergency situation allows you to reduce energy consumption by approx. 0.3 kWh/km. Potentially benefits resulting from the use of heating power modulation were shown in chapter 4.

An important element is also to improve the traffic flow and reduce congestion, thanks to which the transportation speed can increase. This improves not only the attractiveness of public transport for passengers, but also reduces energy consumption (Figs. 7–9). For this reason, it is recommended to introduce separate lanes (bus lines) for public transport vehicles.

Table 6 Shows the list of methods of reducing of auxiliaries energy demand. The reduction of energy consumption of non-traction needs is currently the main challenge related to the reduction of energy demand of means of transport. The energy efficiency of traction drive systems is already close to the maximum (Bartłomiejczyk et al., 2017), while there is a great potential for increasing the efficiency of auxiliary systems.

6. Conclusions

The analysis showed the importance of auxiliaries in the total energy consumption of electric buses. The tests were carried out in a real transport system and are based on many years of experience. Energy consumption for auxiliaries accounts for almost half of total energy consumption, and in the winter it reaches 70% in daily scale. Taking into account the high efficiency of currently operated propulsion systems, the main way to reduce energy consumption in transport is to reduce the energy consumption of auxiliaries.

Optimization of non-traction needs consumption allows to reduce the capacity of traction batteries by 20–50%. This brings with it a reduction in the vehicle price and an increase in passenger capacity. Bearing in mind the difficult to determine change of battery prices in the future, we should try to minimize their capacity.

Table 6
Comparison of solutions which can be useful in reducing of energy demand of auxiliaries.

Technical solutions	Using an intelligent management of auxiliaries - increasing of its power during regenerative breaking Taking in a consideration of load time characteristic (mainly IMC systems) Improvement of the thermal insulation of the vehicle Using heat pump
Operational aspects	Passenger habits, optimization of inside temperature Precisely adjusting of inside temperature, avoiding overheating Reducing of inside temperature in emergency situations Reduction of heating power during breaks and technical pauses Improve the traffic flow and reduce congestion - individual bus lines, priority on road crossings

An important issue is also increasing the smooth flow of public transport traffic. This can be done by giving priority to buses, the use of dedicated lanes for public transport and the use of intelligent traffic control systems (ITS). This is important from the point of view of transport energy, because it allows to reduce the energy demand and reduce the required traction battery capacity.

In cities with a very cold climate, it is reasonable to use oil heating. An alternative can also be dynamic charging, in which it is possible to increase the heating power on sections equipped with traction cathenary (or another linear charging system) and its limitation on sections without the cathenary. In other words, dynamic charging of electric buses is a method of reducing the capacity of traction batteries. In this case, it is useful to use the time characteristics presented in the article for optimizing battery capacity.

Better prediction of the energy demand would improve the reliability of electric bus operation and reduce unnecessary to put in service additional vehicles due to concurrent recharging events, The characterization of energy demand under uncertainty can also help in sustainable route planning.

Appropriate management and control of energy consumption by non-traction needs of vehicle enables to reduce the energy demand with possibly minimal deterioration of the travel standard. In many cases, it can also increase travel comfort by limiting the overheating of the vehicle. Taking into account the development of the popularity of electric buses, this is a significant improvement in the development of electromobility. The electromobility gradually becomes a part of sustainable development of modern cities, so due to the high impact of non-traction loads on total energy consumption, this issue is very important. Proper technical solutions used to supply non-traction loads allows not only to reduce energy consumption, but giving good chance to reduce the price of vehicles (lower battery size at same or increased charging capacities) and improve the operational parameters (increased the autonomy of vehicles).

Autors contribution

Robert Kołacz: chapter 3.2.2: “Influence of timetable adherence – Tristar system”, preparing of the answers for Reviews for the 1st revision.

Mikołaj Bartłomiejczyk: all rest of the work.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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