Energy Consumption in Tram Transport

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Rail transport through the use of electric traction is more friendly for environment than other means of transport. It has a lot of benefits, mainly: the possibility of mass transport using as little energy as possible per one passenger, reducing crowd, reducing congestion, lower emission of pollution, weatherproof, more safety, regularity of travelling. As we can see from the above mentioned benefits, public tram transport is one of the most popular means in Poland.
Tram market in Poland is one of the largest in the world. Nowadays we have 14 thousand tram lines used by 16 companies, which gives a total of above 3600 cars. We have many types of trams exploited at present. The most popular are cars 105Na, characterized by low comfort for passengers, too low durability and high energy consumption. Because these cars are at present exploited, on the basis of their structure many different modernizations are made. The examples could be two types of cars : 204WrAs and 205WrAs , which have been produced since 2005 by the Wrocław PROTRAM Company.
The largest Polish cities also use a modern trams stock produced by the largest Polish construction companies. One of the examples is recently using five-cars type 120Na produced by PESA company.
This article presents results of measurements of energy consumptions of trams 105Na using traditional start –up resistance and trams PROTRAM 205WrAs type with asynchronous propulsion system in IGTB technology. Then the energy consumption is compared with data obtained from manufacturer of a modern tram PESA 120Na, working in the same conditions – asynchronous propulsion system.
Keywords: tram, energy consumption, measurements.

1. INTRODUCTION

The trams 105Na type are the main stock exploited in transport by Polish Transport Companies. In the classical resistance drive system adopted in tram 105Na power traction motors are powered by resistance drive called starter drum [1,2]. This is an outdated method, energy-consuming, uneconomic and unused in modern cars. Apart from trams using classical resistance drive system, improved trams with asynchronous drive are characterized by significant reduction of both costs of energy and operation, as well as increase in reliability [3].

This article presents energy reduction in cars type 105 compared with classical drive system, car type 105 after modernization e.g. replacement of starting resistance based on IGBT with asynchronous propulsion and new trams cars such as PESA 120Na.

2. METHODS OF MEASUREMENTS OF ENERGY CONSUMPTION

In order to determine the size of energy consumption for trams of series 105 after and before modernization there were measured of absorbed power.

2.1. MEASURING DEVICES

The analysis of energy consumption was measured using direct current electricity meters LE3000 plus Elester PKP Company (fig. 1). Electricity meters LE3000 plus is state of the art of traction power and electricity in power supply systems, as well as direct current electric traction vehicles.

Standard measurements of the current electricity meters can be read directly on the display device, locally via USB and remotely by direct request transmission using GPRS in the GSM network and periodically stored on FTP server. The purpose of the communication unit (KOM) of the LE 3000plus meter is to process, present and record the data received from the measuring unit, and to communicate when a remote readout is needed. The data from the meter may be read locally using a USB port and a dedicated software provided by the manufacturer, or remotely via GPRS transmission (upon user's request) and periodically to an FTP server. LCD display of the LE3000plus KOM module presents current values of the voltage and current being measured as well as power counters' readings, thanks to that the meter is simultaneously a panel meter for main circuit parameters. Moreover, it is possible to exchange data with other onboard instruments via CAN or RS-485 interfaces.

Fig.1. Current electricity meters used in measurements

Current electricity meters cooperate with the main electrical system in order to obtain total energy consumption of a vehicle. Standard version, the electricity meter LE 3000plus consists of three basic elements:

- shunt for current measurement in the main circuit,
- measuring unit (high-voltage),
- communication unit (low-voltage).

It was installed in the circuit between the pantograph and the main voltage of trams. By this method, measurements of total energy consumption of a car (fig.2) were obtained .

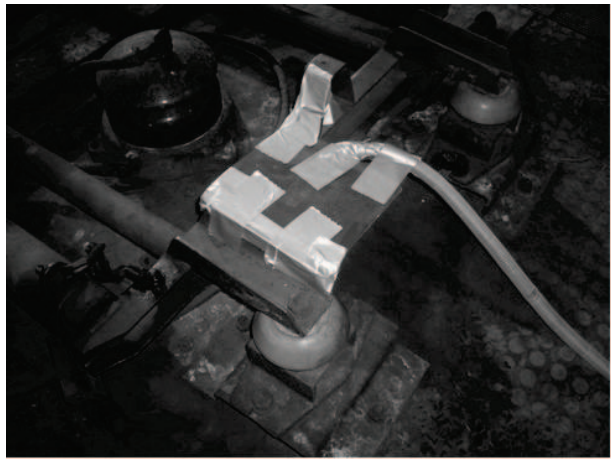

Fig. 2 Outer measuring shunt mounted in pantograph

High – voltage measuring (fig. 3.) was connected to shunt, while part of measurements with high-voltage part was connected to optical fibers. Current electricity meters were made with accuracy class 0,5.

Fig. 3. High-voltage part of current electricity meters

3. STAGES AND VARIANTS OF MEASUREMENTS

Measurements were divided on two parts:

- measurements of cars before modernization (W1-W8)
- measurements of cars after modernization(W1Z- W2Z)

3.1. MEASUREMENTS OF ENERGY CONSUMPTION IN CARS 105 TYPE BEFORE MODERNIZATION

Measurements of energy consumption carried out for cars 105Na type using classical drive system. For this test were chosen trams of 105Na type marked no. 725-736. Measurements carried out in two parts. In the first part there were carried out driving tests with multiplicity i.e. in combination with other separate car 105Na. To simulate the load occurring in normal operating conditions , cars while driving were loaded with sandbags (lines 7 and 16). The routes were selected in terms of length and also inclination of the track. Tram line no 7 amounts about 19,5 km and has so flat edge. Tested route has 37 tram stations. The start of the route is in Katowice – Szopienice, then trough Zawodzie, center, Załęże, Chorzow, Swietochłowice, and ends up in Bytom on tram stations Łagiewniki Targowisko (fig. 4.)

Fig.4. Schematic route of tram line no 7

The tram line no 16 is completely different. Apart from line 7,line 16 amounts about 5,9 km, with different grade (draw 5). This line is characterized by different grade including two sections with substantial grade as the city tram line. The first section is localized between Koszutka Misjonarzy Oblatow and Katowice Rondo tram stations. The second from tram stations Katowice Rynek to tram stations Katowice Stadion AWF. The line no 16 has 12 tram stations.

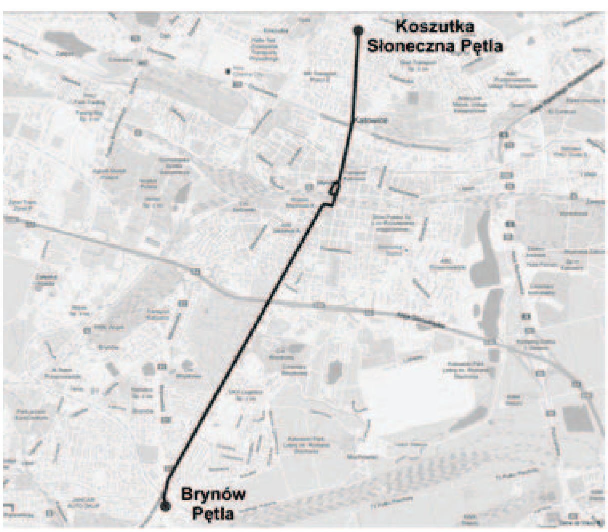

Fig. 5. Schematic route of tram line no 16

The test drives were tested based on the line no 7 and no 16, the traveling took place behind normal line car. Tested tram was being stopped on the each tram stations simulating normal drive. All test driving were carried out by the same driver`s. Driving in main direction took place with turned up heating in passenger cabin, (line 7 – direction Łagiewniki Targowisko, line 16 – direction Brynów Pętla), while in opposite direction with turned off heating (line 7 – direction Szopienice, line 16 – direction Słoneczna Pętla).

3.2. MEASUREMENTS OF ENERGY CONSUMPTION BY CAR 105 SERIES AFTER MODERNIZATION (205WRAS)

The next step of investigation were measurements of energy consumption of cars type 105 after modernization (205WrAs) with asynchronous drive. Because of the lack of the car this type by Tramwaje Śląskie Company, tests were carried out in Wroclaw in cooperation with MPK Wroclaw Company. For these measurements was chosen tram 205WrAs type. Test carried out on tram no2 on line Krzyki-Biskupin (fig. 6). The tram line no2 was selected on the basis of detailed analysis of lines in Wroclaw. The line has almost the same driving resistance, as Tramwaje Śląskie system. On the route line are localized 16 tram stations. The line length is 10,8 km.

Fig. 6. Schematic route of tram line no2 in Wroclaw

3.3. VARIANT OF ANALYSIS

Variant 1

Double car type 105Na (725-726) of line no 7 (Szopienice Pętla – Świętochłowice Łagiewniki) with heating turned up.

Variant 2

Double car type 105Na (725-726) of line no 7 (Szopienice Pętla – Świętochłowice Łagiewniki) with heating turned off.

Variant 3

Double car type 105Na (725-726) of line 16 Katowice Brynów Pętla – Katowice Słoneczna Pętla) with heating turned up.

Variant 4

Double car type 105Na (725-726) of line 16 Katowice Brynów Pętla – Katowice Słoneczna Pętla) with heating turned off.

Variant 5

A single car type 105Na (725) of line no7 (Szopienice Pętla – Świętochłowice Łagiewniki) with heating turned up.

Variant 6

A single car type 105Na (725) of line no7 (Szopienice Pętla – Świętochłowice Łagiewniki) with heating turned off.

Variant 7

A single car type 105Na (725) of line no 16 (Katowice Brynów Pętla – Katowice Słoneczna Pętla) with heating turned up.

Variant 8

A single car type 105Na (725) of line no 16 (Katowice Brynów Pętla – Katowice Słoneczna Pętla) with heating turned off.

Variant 1Z

Open space passengers compartments 205WrAs of line no 2 (Krzyki-Biskupin) with warning turned up.

Variant 2Z

Open space passengers compartments 205WrAs of line no 2 (Krzyki-Biskupin) with warning turned off.

4. MEASUREMENTS OF ENERGY CONSUMPTION

Obtained measurements of energy consumption were showed in table 1.

Table 1. Measurements of energy consumption

No.	Variant of route	Value of energy consumption kWh	Value of consumption [kWh/km]	Value of consumption kWh/ 1carkm*)
1.	V1	131	6,72	3,36
2.	V2	96	4,89	2,45
3.	V3	46	7,93	**3,97**
4.	V4	36	6,05	3,03
5.	V5	71	3,64	3,64
6.	V6	52	2,65	2,65
7.	V7	24	4,14	4,14
8.	V8	21	3,53	3,53
9.	V1Z	55	6,28	3,14**
10.	V2Z	34	4,34	2,17**

*) consumption of energy in kWh per one carkm

** value divided by two because one car type 205WrAs equal car 2x105Na

As the above table shows, the highest consumption for trams of 105 type (before modernization) calculated in car/km was observed for Variant V3 i.e. on route Katowice Pętla Słoneczna – Katowice Brynów Pętla. While for Variant V6 on route Szopienice Pętla – Świętochłowice Łagiewniki with heating turned up the lowest energy consumption was observed. Generally of all analysis variants, the lowest energy consumption was observed in tram after modernization V2Z (with heating turned off).

5. ANALYSIS OF ENERGY CONSUMPTION FOR TESTING VARIANTS

The average energy consumption on traction requirements (without heating) for trams of 105 type (before modernization) amounts 2,9kWh/1carkm. The average energy consumption on traction requirements (without heating) for trams of 105 (after modernization) amounts 2,17 kWh/1carkm. Analyzing of these results we can say that turned up heating in car causes a significant increase of energy consumption.

Tram of 105 (before modernization) has the following power of heating equipments:

- 10 items resistance convection heaters with power 700W each, located in passengers compartments;

- 8 items de-icers (heating glass) with power 250W each, located in driver's cab
- 1 resistance convection heaters with power 1000W located in driver's cab

Therefore the total power of heating in one car of 105 amounts to 10KW. The average speed on the area of Tramwaje Slaskie amounts about 15-16 km/h. When we know these values we can determine theoretical energy consumption consumed by heating in car on 1carkm, that amounts to about 0,7 kWh. These values correspond to variants showed in table 2.

Table 2. Energy consumption during heating car

No.	Variant of route	Value of consumption kWh/ 1carkm*)	Energy consumption to heating kWh/ 1carkm
1.	V1	3,36	0,915
2.	V2	2,45	
3.	V3	3,97	0,940
4.	V4	3,03	
5.	V5	3,64	0,990
6.	V6	2,65	
7.	V7	4,14	0,610
8.	V8	3,53	
9.	V1Z	3,14**	0,970**
10.	V2Z	2,17**	

** value divided by two because one car type 205WrAs equal car 2x105Na

For example energy consumption for variant V7 and V8 amounts 4,14kWh with heating and 3,53 without heating. So energy consumption of heating in this type of variant amounts 0,61kWh. Analogously, energy consumption of heating for variants V1 and V2 amount about 0,9 kW. The difference in energy consumed by heating is caused by duration of travelling. The average length used by heating for tram of 105 type (before modernization) amounts 0,86kWh/1wzkm. Cars 205WrAs that use asynchronous drive consume less energy, than classical cars type105Na. In this case consumption amounts 3,14 kWh/1carkm with heating and 2,17 kWh/1carkm without heating. Cars **of** 205WrAs type have 8 heaters with power 3kW each allocated in passengers compartments and 1heater with 3kW allocated in driver's cab. The total heating power in this tram amounts 21kW. According to results of measurements energy consumption we can say that energy consume during heating amounts 0,97kWh/carkm. These results are comparable with variants V1 – V6.

6. DETERMINATION OF AVERAGE ENERGY CONSUMPTION BY TRAM OF 105 (BEFORE MODERNIZATION)

In the Tramwaje Śląskie the average annual traveling of car of 105 amounts about 78000 km/year. Calculating a month it is 6500km/month (data obtained from Tramwaje Śląskie Company). Tramwaje Śląskie under a contract with KZKGOP is required to turn up heating, if temperature amounts below 0ºC. Cars series 105 have gradation of power heating. For the purpose of calculations it can be assumed that the heating is turned up for 3 months/year at full power 10kW. We can conclude - the average yearly energy consumption by tram of 105 (before modernization) will amount [4]:

$$RZE_1 = 9 \cdot Pm \cdot z_e + 3 \cdot Pm \cdot z_{eo} \qquad (1)$$

where:

RZE_1 – yearly energy consumption by one tram type 105 before modernization [kWh]

Pm – the average monthly traveling for type 105 [km/month]

z_e – the average energy consumption calculating per 1carkm by tram type 105 before modernization without heating [kwh/1carkm]

z_{eo} – the average energy consumption per 1carkm by tram type 105 before modernization with heating [kwh/ 1carkm]

Assuming the following data:

Pm – 6500 km/month

z_e – 2,9 kWh/1wzkm

z_{eo} – 2,9 + 0,86 = 3,76 kWh/1wzkm

Yearly energy consumption by tram type 105 before modernization (RZE_1) amounts 242970 kWh, approximately **0,243GWh**.

7. DETERMINATION OF AVERAGE ENERGY CONSUMPTION BY TRAM OF 105 (AFTER MODERNIZATION)

Assuming analogous procedure for modernized trams it can determine the average annual electricity consumption, which is [4]:

$$RZE_2 = 9 \cdot Pm \cdot z_{e2} + 3 \cdot Pm \cdot z_{eo2} \qquad (2)$$

where:
RZE_2 – yearly energy consumption by one tram type 105 after modernization [kWh]
Pm – the average monthly travelling for type 105 [km/month]
z_e – the average energy consumption calculating per 1carkm by tram type 105 after modernization without heating [kwh/1carkm]
z_{eo} – the average energy consumption per 1carkm by tram type 105 after modernization with heating [kwh/ 1carkm]

Assuming the following data:
Pm – 6500 km/month
z_{e2} – 2,17 kWh/1carkm
z_{eo2} – 2,17 + 0,97 = 3,14 kWh/1carkm

Yearly energy consumption by tram of 105 type after modernization (RZE_2) amounts 188175 kWh**,** approximately **0,188GWh.**

8. DETERMINATION OF AVERAGE ENERGY CONSUMPTION BY TRAM OF 120NA TYPE

Information on energy consumption of tram of120Na type were obtained from measurements carried out by PESA Bydgoszcz, make on area of Tramwaje Warszawskie. The measurements concern the total consumed energy by tram.

The measuring system was instaled in pantograph system. For this research selected car of 120Na 1SWING no 3121 type. Measurements carried out on linear trams during 3 months by different driver`s. The average energy consumption for driving (without heating) for tram type 120Na amounts 4,1kWh/1carkm. While energy consumption with heating amounts 5,3 kWh/1carkm. Tram type 120Na is equipped with recuparation of energy system, but its using depend on loading overhead lines.

In the following calculation, the value of recuperated energy has been omitted.

When we know the above data, we can determine the average yearly energy consumption of a tram series 120Na, which gives [4]:

$$RZE_3 = 9 \cdot Pm \cdot z_{e3} + 3 \cdot Pm \cdot z_{eo3} \qquad (3)$$

Where :
RZE_3 – yearly energy consumption by tram type 120Na [kWh]
Pm – the average monthly travelling for type 120Na [km/month]
z_{e3} – the average energy consumption calculating per 1carkm by tram type 120Na without heating [kWh/1carkm]
z_{eo3} – the average energy consumption per 1carkm by tram type 120Na with heating [kwh/ 1carkm]

Assuming the following data:
Pm – 6500 km/month
z_{e3} – 4,1 kWh/1carkm
z_{eo3} – 5,3 kWh/1carkm

Yearly energy consumption by tram type 120Na (RZE_3) amounts 343200 kWh, approximately **0,3432GWh.**
Because capacity of tram 120Na is twice big as car type 105 therefore to compare this capacities we should divided value by two.

9. THE PERCENTAGE DETERMINATION OF DIFFERENCE ENERGY CONSUMPTION

Fig. 7 presents comparison of energy consumption. This analysis doesn't include energy recuperation because it depends on travelling conditions. Because of the fact that tram series 120Na has twice capacity as trams series 105 (before and after modernization), all results for trams series 105 were doubled, which the following graph presents.

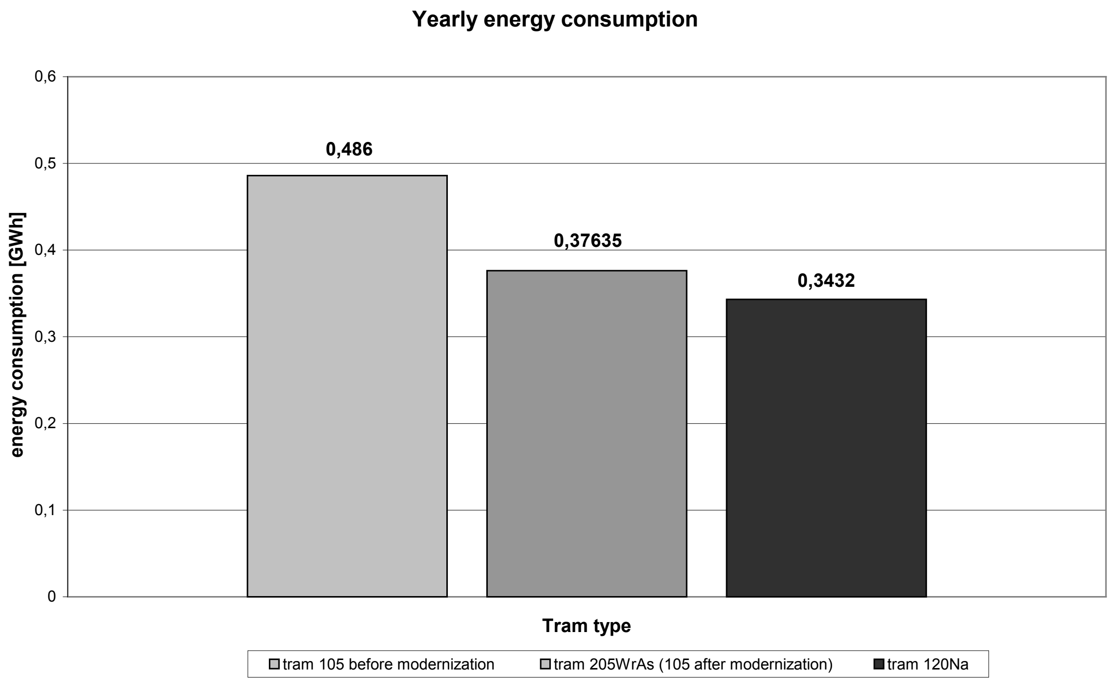

Fig. 7. Comparison of energy consumption

9.1. THE PERCENTAGE DETERMINATION DIFFERENCES OF ENERGY CONSUMPTION BETWEEN TRAMS SERIES 105 BEFORE MODERNIZATION AND AFTER MODERNIZATION

The differences were calculated on the basis of yearly energy consumption. So yearly energy consumption by one car series 105 (before modernization) amounts: RZE_1 = 0,243GWh, but energy consumption by car series 105 after modernization amounts: RZE_1 = 0,188GWh. Therefore the differences in percent can be expressed by the formula:

$$R_1 = \frac{RZE_1 - RZE_2}{RZE_1} \cdot 100\% \qquad (4)$$

Where:

R_1- differences between trams series 105 before modernization and after modernization[%]

RZE_1- yearly energy consumption by one car type 105 before modernization [GWh]

RZE_2- yearly energy consumption by one car type 105 after modernization [GWh]

$$R_1 = \frac{0{,}243 - 0{,}188}{0{,}243} \cdot 100\%$$

R_1 = 22,56%

9.2. THE PERCENTAGE DETERMINATION OF ENERGY CONSUMPTION COMPARING TWO CARS TYPE 120 AND 105 BEFORE AND AFTER MODERNIZATION

Percentage differences of energy consumption calculated on the basis of yearly energy consumption by tram type Pesa Swing 120Na. And so yearly energy consumption by double tram series 105 (before modernization) amounts: RZE_1 * 2 = 0,486 GWh, while consumption by tram 120Na amounts: RZE_3 = 0,3432 GWh. Thus the differences can be expressed by the formula:

$$R_2 = \frac{2 \cdot RZE_1 - RZE_3}{2 \cdot RZE_1} \cdot 100\% \qquad (5)$$

Where:

R_2- yearly energy consumption between cars types 105 and 120 Pesa [%]

RZE_1- yearly energy consumption by one car 105 before modernization [GWh]

RZE_3- yearly energy consumption by tram 120Na [GWh]

$$R_2 = \frac{2 \cdot 0{,}243 - 0{,}3432}{2 \cdot 0243} \cdot 100\%$$

R_2 = 29,38%

10. CONCLUSION

For technical reasons measurements of energy consumption for various types of trams were carried out in different cities. In the case of measurements carried out in Wroclaw and Katowice driving conditions on the testing section were the same. However measurements for car 120Na were carried out during the normal operation of tram and as a result, these measurements should be considered as the most appropriate.

The measurements of energy consumption were carried out by using two trams operating with different drive systems. The first was a tram Konstal 105Na before modernization with classic resistance system, and the second Protram 205WrAs with asynchronous propulsion system. The results showed that the replacement of the classic drive system with asynchronous propulsion system in IGTB technology causes reduction in energy consumption.

Trams type 205WrAs use less energy than classic trams type 105Na, the average 0,69 [kWh/1carkm] less, that gives about 23 (%).

Average energy consumption for tram 105Na without heating amounts 2,91 [kWh/1carkm], while with heating 3,78 [kWh/1carkm]. Average energy consumption for tram 205WrAs without heating amounts 2,17 [kWh/1carkm], while with heating 3,14 [kWh/1carkm]. Apparently, the heating turned up in cars causes significant increase in energy consumption. In tram 105Na average of 0,86 [kWh/1carkm], that is about 29 (%), while in tram 205WrAs average of 0,97 [kWh/1carkm], that is about 44 (%)

The analysis for comparative purposes also includes energy consumption of modern Tram cars. Analysis included data obtained from the producers of trams Pesa 120Na.

Compared the average yearly energy consumption it turned out that the least energy consumed car type 120Na 0,343 [GWh], and most car type 105Na – 0,488 [GWh]. For a car type 205WrAs the yearly energy consumption amounts 0,376 [GWh].

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