Comparison of different tram cars in Poland basing on drive type, rated power and energy consumption

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Abstract. Paper deals with tram rolling stock used in Poland nowadays – overview of car types in operation is given. The detailed calculations of energy consumption by a given tram car running over a given route depend in particular on the work carried out (each route is characterized by, among other factors, its profile, length, number of turns, turn radii, number of stops – scheduled or otherwise, number of transferred passengers, number of brakings with possibility of energy recuperation). Results of energy consumption measurements for different car types in Warsaw are provided and analysed.

1 Tram cars used in Poland

Number of tram cars used in Polish cities is shown in Table 1 [1-4]. In case of popular 105Na trams we differentiated between not modernized and modernized cars whenever possible (modernized in this case means the replacement of standard resistor start-up and speed control circuit with a power electronics device).

Table 1. Tram rolling stock in Polish cities.

City	No. of 105Na cars and their variants* (additional number of modernized cars is given in brackets)	Number of relatively new cars **	Number of other cars***
Warszawa	257 (135)	341	-
GOP	105 (108)	67	40
Gdańsk	34	49	60
Wrocław	92 (168)	103	-
Poznań	61 (20)	109	37
Toruń	55	17	-
Olsztyn	-	15	-
Bydgoszcz	112	14	-
Częstochowa	44	7	-
Elbląg	17 (3)	6	6
Grudziądz	8 (6)	-	10
Szczecin	6 (26)	102	73
Gorzów Wlkp.	-	-	20
Kraków	72	152	172
Łódź	238 (246)	48	29

* Tram cars with dc drives and resistor start-up
**Models such as 122NaL *Swing*, 121N *Tramicus*, *Combino*, S105p *Tramino*, Tatra RT6, 2010NW *Twist,* 116Nd *Citadis*, 16T, 19T, 204WrAs and others, not older than 25 years
***Models such as Duewag M8C, M6S, GT6, GT8N, E1, Pt8, Ptm and others, manufactured e.g. 1962-67, 1972-77, 1978-86, mostly modernized, bought second-hand

2 Energy consumption in a selected tram company

Most electrical energy is used by traction drive system. The remainder goes to heating, air-conditioning when present, lighting, control circuits, auxiliaries. The values set out in Tables 2-4 are calculated from data obtained from biggest tram operator in the country, i.e. Warsaw Tram Company [5]. Total length of tram tracks is c. 280 km. Each tram in Warsaw is equipped with energy measurement device, the new trams with digital recorders. Energy consumed by trams is equal to c. 94.7% of total electrical consumption in this company (2015). The oldest tram cars running in Warsaw date back to 1984, average car is almost 15 years old (*cf.* Table 1). Warsaw tram stock is detailed in Table 2.

Table 2. Tram stock in Warsaw: drive type, energy recuperation possibilities.

Car type	Number of cars	Start-up and control/motor ratings	Energy recuperation/ storage
105Na	257	resistor start-up/4 x 41.5 kW	no/no
105Ni	26	converter/4 x 41.5 kW	yes/no
105N2k	47	converter/4 x 41.5 kW	yes/no
105Nk/ 2000	62	converter/4 x 41.5 kW	yes/no
123N	30	converter/4 x 41.5 kW	yes/no
112N	1	converter/6 x 41.5 kW	yes/no
116Na 116/Na1	29	inverter/4 x 50 kW	yes/no
120N	15	inverter/4 x 105 kW	yes/no
120Na	180	inverter/4 x 105 kW	yes/no
120Na DUO	6	inverter/4 x 105 kW	yes/no
128N	50	inverter/4 x 105 kW	yes/ ultracapacitor 425VDC
134N	30	inverter/8 x 60 kW	yes/ ultracapacitor 400VDC

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Relatively large portion of energy goes to heating and air-conditioning circuits - see Table 3.

In newer trams, in particular 120N series and its variants, 128N and 134 N cars, the ratio of heating/a.c. power to car volume is on the average 2.5-3 times higher than in cars 105Nx, 112N, 123N and 116Nx.

Energy consumed by drive systems varies from c. 67% (123N) to c.83% (120N/Na), while auxiliaries' energy varies from c.19% to c.10%, respectively (see Table 4).

Table 3. Comparison of drive and heating/air-conditioning circuit ratings.

Car type	Total heating/a.c. power in kW	Ratio of heating/a.c. power to motor power in %	Indicator of heating/a.c power per car volume in kW/m^3
105Na	12.2/3.5	7%	0.12
105Ni	13/3.5	8%	0.13
105N2k	10.9/3.5	7%	0.11
105N2k/2000	14.2/3.5	9%	0.14
123N	20/3.5	12%	0.18
112N	19.2/3.5	12%	0.12
116N/116Na/116N/1	24.8/3.5	12%	0.13
120N	85.1/49.1	20%	0.33
120Na	75/64	18%	0.31
120Na DUO	80.4/64	19%	0.33
128N	84.4/55	18%	0.35
134N	42.4/40.5	9%	0.27

Table 4. Drive and auxiliary circuits' energy participation in total energy consumed by a tram car.

Car type	Energy consumed by motors	Energy consumed by auxiliaries
105Na	76.2%	16.2%
105N2k, 105N2k/2000	74.2%	17.6%
112N	74.2%	17.6%
116Na, 116Na/1	77.9%	13.2%
123N	67.6%	19.4%
120N/Na	82.8%	10.2%
128N	82.8%	10.2%
134N	82.0%	10.8%

Analysis of energy used for traction purposes was carried out not in terms of total energy consumption but using indicators. e.g. referring energy to the distance per car (unit: car-kms), to vehicle weight (empty car, partial or full load) and finally, to number of passengers transferred. In practice, the indicators related to number (weight) of passengers and not those referring to car-kilometres make it possible to compare energy consumption by different cars in a rational manner. The indicators are set out in Table 5 and shown graphically in Fig.1.

Tram cars 120N and 128N consume more energy by other cars; their consumption is even greater than in case of 105Na – 105Nm cars, which cannot recuperate braking energy back into the network. This phenomenon is due to the fact, that carrying capacity is greater, which results in greater weight of the vehicle. 120N and 128N type cars' weight without passengers (hereafter this will be called weight of empty cars) is also much higher than that of other cars. Therefore, during following comparisons, we took into account number of passengers transferred.

Analysing weight of empty cars and weight of cars with passengers, we determined several intervals for total vehicle weight (car carrying 40%, 70% and 100% of maximum number of passengers, i.e. 40%, 70% and 100% of total carrying capacity). The tram weight per one passenger for these different loads is shown in Fig.2. The smallest weight relates to 100% load, the points marked refer to 70% load, and highest weight per one passenger related to 40% load.

Table 5. The analysed data - energy consumption and car weight.

Car type	Car weight without/ with passengers	Energy consumed (at panto-graph)	Energy consumed by drive system	Recuperated energy	Energy consumed by drive system. recuperation included
	tons	kWh/km		%	kWh/km
105Na.. 105Nf	16.8/25.55	no data	2.50	none	2.50
105Ni	17.5.26.25	1.97	1.91	28.79% *	1.36
105N2k	17.7/26.45	no data	1.91	28.79% *	1.36
105N2k /2000	17.7/26.45	2.17	1.91	10.17% *	1.72
123N	18.2/24.99	no data	1.91	28.00%	1.38
112N	26.0/40.28	no data	3.23	28.00%	2.33
116N	29.0/44.05	no data	3.23	28.00%	2.33
116Na	29.0/44.05	no data	3.23	28.00%	2.33
116N/1	29.0/44.05	no data	3.23	28.00%	2.33
120N	43.4/58.17	no data	4.37	28.00%	3.15
120Na	40.6/55.04	5.7	4.37	29.87%	3.06
120Na DUO	42.7/56.375	5.7	4.37	29.87%	3.06
128N	41.5/56.195	5.45	3.96	29.88%	2.78
134N	30.42/39.45	3.97	2.92	31.45%	2.00

* Ratio of energy recuperated into the network to total energy supplied to the tram car (at pantograph)

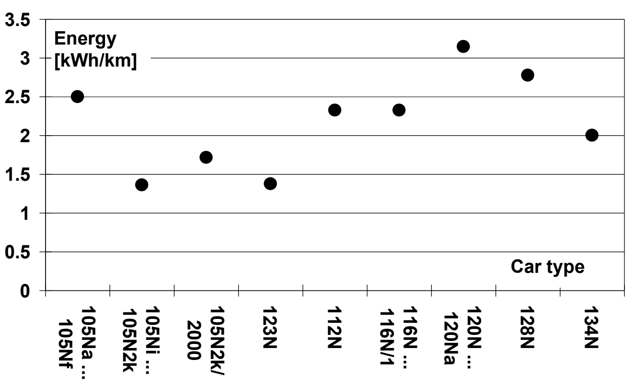

Fig. 1. Energy consumed by drive system – per 1 km of distance, for different cars.

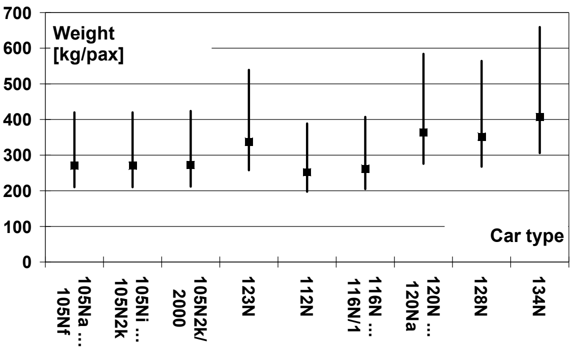

Fig. 2. Weight intervals per one passenger, for different car types. Points refer to 70% load, smallest weight to 100% load, highest weight to 40% load.

120N and 128N tram cars are characterized by higher weight per one passenger than other cars, this is due to the weight of empty cars (i.e. without passengers). Low-floor trams 120N - 134N are equipped with air-conditioning systems for passengers, which improves travel comfort in the summer, but increases vehicle weight at the same time. Cars 128N - 134N are fitted with on-board ultracapacitor storage systems, this also increases vehicle weight. The energy consumed by the drive system has been related to total vehicle weight, taking into account the varying load (see Fig.2). Energy consumption intervals have been determined, for load varying from 40% to 100% of carrying capacity. Energy consumed per 1 km of distance and per 1 ton of car weight is shown in Fig.3. As before, lowest consumption relates to maximum (100%) load, marked points correspond to 70% load and highest consumption occurs, when 40% of tram's carrying capacity is used.

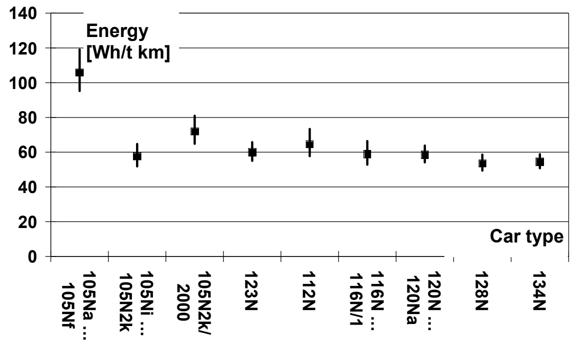

Fig. 3. Drive system energy consumption intervals related to 1 ton of car weight and 1 km of distance, for different trams. Points refer to 70% load, smallest weight to 100% load, highest weight to 40% load.

Tram cars which are able to recuperate energy (105Ni - 134N) are characterized by much lower energy consumption per 1 km of distance and 1 ton of car weight (from *c*. 95 to 130 Wh/tkm) than cars without recuperation. i.e. 105Na – 105Nm (from *c*.50 to *c*.87 Wh/tkm) - see Fig.3.

Next, we calculated energy consumed in relation to 1 passenger, 1 ton of car weight and 1 km of distance. Calculations have been run for load ranging from 40% to 100%. Energy consumed per 1 passenger, 1 ton and 1 km is shown in Fig.4. The lowest consumption corresponds to 100% load, the highest to 40% load and the points refer to 70% tram load.

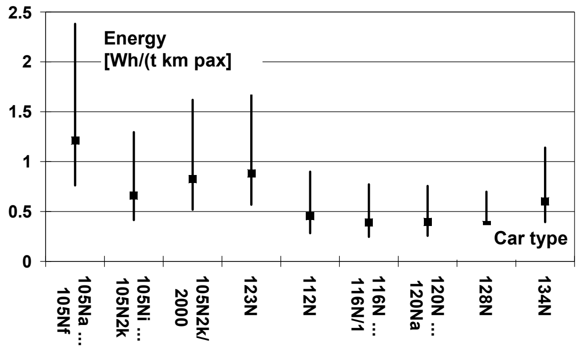

Fig. 4. Drive system energy consumption intervals related to 1 passenger, 1 ton of car weight and 1 km of distance, for different trams. Points refer to 70% load, smallest weight to 100% load, highest weight to 40% load.

Tram cars which are able to recuperate energy (105Ni - 134N) are characterized by much lower energy consumption per 1 passenger, 1 km distance and 1 ton of car weight than cars without recuperation - see Fig.4. The heavier trams (120N - 134N) equipped with air-conditioning of passenger compartments are characterized by low consumption related to 1 passenger, 1 km of distance and 1 ton of car weight.

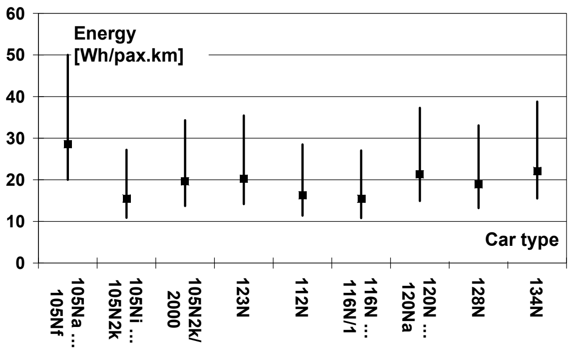

Fig. 5. Drive system energy consumption intervals related to 1 passenger and 1 km of distance, for different trams. Points refer to 70% load, smallest weight to 100% load, highest weight to 40% load.

We have also calculated energy consumption per 1 passenger and 1 km of distance (kWh/pax.km). The calculations were carried out for load varying from 40% to 100% of total carrying capacity. The energy consumption per 1 passenger and distance of 1 km is shown in Fig.5. As before, lowest consumption relates to maximum (100%) load, marked points correspond to 70% load and highest consumption occurs, when 40% of tram's carrying capacity is used.

Tram cars which are able to recuperate energy (105Ni - 134N) are characterized by much lower energy consumption per 1 km of distance and 1 passenger, than cars without recuperation. i.e. 105Na – 105Nm. Low-floor trams 120N - 134N are equipped with air-conditioning systems for passengers and show greater energy consumption per 1 passenger and 1 km than tram cars with energy recuperation possibilities, but without air-conditioning systems. This is due to the value of empty car weight.

3 Some observations on tram car energy consumption calculations

Publications on the subject present different procedures for energy consumption. Exemplary data for trams running in Poland are given by Kuminek [6]. He analysed energy consumption for 105Na cars with resistor start-up and speed control, for routes in Silesian agglomeration, for modernized 205WrAs tram cars running in Wrocław as well as manufacturer's data for 120Na tram cars. He differentiated between energy consumed by cars with heating on and off. The appropriate data for 105Na car is 2.45-4.14 kWh/1 car-km, 2.17-3.14 kWh/1 car-km for 205WrAs and 4.1-5.3 kWh/1 car-km for 120Na car. It must be pointed out that these calculations did not account for the actual tram load (i.e. passenger weight) and that measurements were carried out at different routes.

In Cracow the measurements were carried out by experts from Technical University of Cracow [4], energy consumption varied from 3.2 kWh/car-km for N8 tram cars to 6.3 kWh/car-km for 105Na cars. NGT6 tram (without energy recuperation) shows energy consumption lower by 11-28% than 105Na car and taking into account passenger loading capacity this value is c.26% [7,8].

Tackoen et al. [9] have approached the energy saving issue by way of simulation. They adopted a particular route of a given tram in Brussels and analysed different variants of energy storage on-board systems (ultracapacitors with different capacitance and weight). They calculated possible savings taking into account varying load of the tram. The energy consumption indicator was 5 kWh/km, and possible savings equalled 24% (average value).

Chymera et al. [10] analysed possibilities of improving energy consumption by using ultracapacitors. In order to conduct calculations, they measured energy consumed by 22-ton tram car of City Class operating in Blackpool. The total energy consumption indicator was equal to 1.1 kWh/km, and *c.* 0.75 kWh/km was appropriated by the drive system (motors, converter, dynamic braking circuit, gear). The authors did not account for different loading of the tram. However, in another paper [11] they compared the data for City Class tram car equipped with asynchronous motors, with length equal to 29 m, weighing 22 tons, and with loading capacity of 200 passengers, while older type tram (Centenary Tram) with dc motors and comparable weight (17.5t) may carry 74 passengers only. They also considered possible weight (number of passengers transferred) of the compared cars. The respective indicators for 4 drive cycles were: for City Class tram car from 0.0085 to 0.0098 kWh/pax.km, for Centenary Tram from 0.0194 to 0.026 kWh/pax.km. These values result from simulations carried out for a given route.

Erd et al. [12] analysed possibilities of lessening energy consumption in tram by applying flywheels (rotating energy storage devices). They used data for Variobahn tram (6 motors, 95 kW each, carrying capacity 240 passengers) provided by Bombardier company (distance 17.6 km, route in Heidelberg city). The calculated indicators were 4.21 kWh/km for tram without storage and 3.33 kWh/km for tram with flywheel. Again, the varying passenger load was not accounted for.

4 Applications of energy saving strategies

Polish operators and Warsaw Tram Co. in particular at present investigate different ways of possible reduction in energy consumption. This coincides with current world and European trends in public transportation approach.

An overview of different energy recovery strategies in public transport has been given in [13]. Strategies have been classified in accordance with mobility (mobile storage applications such as on-board energy storage systems, stationary storage applications and stationary applications related to grid). Technologies such as batteries, ultracapacitors, flywheels and reversible substations are presented together with examples of prototypes designed and operating in public transport sector. However, the authors point out that apart from the mobile storage systems (ultracapacitors mostly), most of possible solutions have not yet been implemented on a mass scale.

Henning et al. [14] discuss in detail two options for energy storage in light rail vehicles: flywheels and ultracapacitors. Power densities of ultracapacitors and modern flywheels are similar, but flywheels offer higher energy density, which is better if acceleration times are longer (unit cited here offers 4 kWh, 300 kW at 375 kg compared to double that weight back in 1995).

Destraz et al. [15] have studied impact of ultracapacitor storage and high line resistance on energy consumption in urban trams. Again, modelling has been conducted on the basis of existing line data (track in Mannheim, Germany). They have shown that quality of the line has a powerful impact on overall energy consumption, calculating effects of supercapacitor energy storage on a normal network and "weak" network. The results of actual measurements have shown energy saving equal to *c.*25% on vehicle level.

Some trial runs of trams equipped with batteries able to store energy have been carried out in Warsaw. Battery rated at 80 Ah/600 V was used. Possibilities of energy recovery were interesting (over a 12 km run 12-18 kWh could be recovered); however, life cycle of this battery is set by its manufacturer at 13260 cycles, i.e. four years. Simulations have also been conducted on energy saved due to recuperation for city centre and suburban regions, during peak hours and the remainder of the day. Different possibilities have been investigated. Comparison of energy recovered by different tram types has been made (Cityrunner tram, 805Na tram with induction motors, 805Na tram with dc motor and without energy recuperation). Researchers have also compared possibility of installing inverters or flywheels at the substations [16]. Effects of these two solutions are similar. The best effects are shown for regions where the network is most highly loaded; however, in such regions recovered energy may be taken over by other trams and substation devices are not really indispensable. Use of inverters or flywheels in suburban regions may not achieve significant effects, since the network may show high voltage drops and energy recovered during braking cannot be reliably transmitted.

Among the drawbacks of capacitors, we may point out the significant increase of tram car weight (e.g. EDLC ultracapacitors used in Innsbruck trams, rated at 0.85 kWh/288 kW weigh 820 kg). Similar considerations are true for batteries (e.g. NiMH tried in Sapporo Municipal Transport in 2011, rated at 250 kW/120 kWh, weighed 3200 kg).

Recuperation of energy into national grid is not popular as use of energy storage devices mostly on account of high investment costs. Some trials have been done, in Poland notably in Łódź and Olsztyn in 2014-2016, where inverters rated at 0.5-1MW have been used. No solution has been as yet commercially installed.

Another approach to energy consumption is analysis of the greatest tram load, i.e. traction motor.

A thorough overview of motors for light rail traction applications (and other types of vehicles as well) is given by Gieras and Bianchi [17]. Authors compare motors such as standard cage induction motors, standard PM brushless motors with interior type NdFeB magnets, PM brushless motors with short coil spans, hybrid synchronous motors (utilizing permanent magnets and electromagnetic excitation both), permanent magnet transverse flux motor and switched reluctance motor. Different points of motor and drive construction are considered, such as gear, size, volume, motor weight, inverter power. Comparison is valuable as it is provided for 75 kW brushless motors. Efficiency of induction motor is given as 90% and efficiency for remaining motor types varies from 93% to even 97.6%; weight of IM is given as 272kg and corresponding weights of other motors vary from 147 kg down to 73 kg. Apart from technological drawbacks and higher prices, the permanent magnet motor potential is very high.

Demmelmayr et al. [18] have compared energy consumption of standard induction machine with novel prototype permanent magnet synchronous machine (PMSM). Calculations have been made on a basis of typical time graph for electric city tram (total drive type of about 70 seconds, including acceleration phase, maximum speed, deceleration and standstill). Authors concluded that for this given route energy consumed by PMSM was only 49% of induction machine consumption.

Similar issue has been addressed by Mermet-Guyennet [19]. He shows evolution of motors for electric traction used in French railways: from 1981 DC motor rated at 535 kW and weighing 1560 kg (ratio weight/power 2.9 kW/kg), through 1989 synchronous motor (1130 kW, 1525 kg, 1.35 kW/kg), asynchronous motor of 1994(1020 kW, 1260 kg, 1.23 kW/kg) up to synchronous PM motor of 2004 (800 kW, 768 kg, 0.96 kg/kW).

Permanent magnet machines are used almost exclusively in light-duty hybrid vehicles on account of higher power density and efficiency [20]. Trams utilizing PM motors have been designed and built by Czech company SKODA (ForCity Alfa trams, currently operating in Prague, Czech Republic and Riga, Latvia). These trams utilize 16 PMSM motors (surface-mounted magnets) with maximum power 46.6 kW each. Gears have been eliminated. PM motors have also been developed for high-speed rail such as prototype train AGV (2008).

In Poland PMSM motors have not been so far applied for urban rail vehicles (some trials were done by ALSTOM company for X04 tram, but the project was abandoned).

The principal advantages exhibited by PM motors are continuously cited as high power density and efficiency, simple and robust machine construction, low noise, durability, possible elimination of mechanical gearing, possibility of high overload. However, this potential has not been so far utilized fully, the commercial rail vehicles in operations are few in comparison to standard-drive vehicles.

Since substantial part of the energy consumed goes towards heating and air-conditioning, methods for accurate measurement and comparation of different air-conditioning system energy consumption have been developed by Richter [21] in the course of EcoTram research project. Different measures for reducing energy consumption have been researched, such as stepless heat power control, variable supply of air taken from outside (in accordance with CO2 content inside the vehicle), heat pump, elimination of bypass valve from compressor (variable speed control applied), different refrigerator agents used, different quality of window glazing and sun protection films, different colour of outer tram housing surface, predictive-type control for HVAC modules. Development of more energy-targeted HVAC units may lower energy consumption by up to 30%.

Chymera and Goodman [22] give a workable overview of calculating a rail vehicle performance. They enumerate different factors affecting energy consumption and stress the fact that more and more operators will in future require some simulation of rail vehicle performance over a given route while considering offers for stock purchase. These simulations must take into account diverse features such as unscheduled stops and delays.

In Poland and in accordance with peculiarities of Polish operators, the most immediate measures undertaken in order to reduce energy consumption at present are:

– modernization of existing rolling stock, in particular replacement of dc resistor-controlled drive systems with systems providing possibilities of energy recovery, mostly ac induction motors
– installation of on-board storage ultracapacitor systems.

Other possibilities of energy reduction are extensively investigated but have not been implemented commercially.

5 Conclusions

The highest energy consumption in tram cars is due to drive systems, second place is held by air-conditioning and heating systems. In this paper we have analysed energy consumed by drive motors, using indicators expressed in kWh/km (ranging from 2.50 for 105Nx cars with dc motors, resistor start-up and speed control, to even 5.7 kWh/km for 120Na cars and 3.97 kWh/km for 134N cars with asynchronous motors and inverters allowing for braking energy recuperation back into traction network). When recuperation is considered, these indicators range from 2.50 for 105Nx cars to 3.15 for 120 Na cars and 2.00 for 134N cars.

Any car type provided with energy recuperation, irrespective of drive type is characterized by significantly lower energy consumption related to 1 passenger travelling over 1 km distance. Low-floor cars such as 120N, 120Na and subsequent variants, 128N and 134N having air-conditioning for passenger compartments are characterized by higher energy consumption related to 1 passenger travelling over 1 km distance than tram cars able to recuperate braking energy, but not fitted with a/c systems. This heightened specific energy consumption is due to weight of empty trams. To summarize, in our opinion any comparison of energy consumed by trams must be related to the possible passenger load. Such indicators may be nowadays calculated quite easily for different types of trams, since new vehicles commissioned into service are equipped with complex energy recording systems as well as localization systems and passenger count systems.

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