AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149



Dariusz KARKOSINSKI, *e-mail: dariusz.karkosinski@pg.edu.pl*
*Politechnika Gdańska*
Dominika MACEDONSKA, *dominika.macedonska@wp.pl*
*Politechnika Gdańska*
Natalia KARKOSINSKA BRZOZOWSKA, *natalia.brzozowska@pg.edu.pl*
*Politechnika Gdańska*

pp. 8–22 DOI: 10.17274/AEZ.2020.42.01

# Electric Multiple Units With Energy Storage – Alternative to Electrification of New Lines in Three City[1)]

## Elektryczne zespoły zasobnikowe jako alternatywa dla elektryfikacji nowych linii w Trójmieście

***Abstract:*** *The application of modern EMUs in Trójmiasto has been discussed in the paper. A new line between Gdańsk Śródmieście and Orunia Górna has been proposed as well as the reconstruction of lines running to northern quarters of Gdynia. Trójmieście transport system has been analysed from the viewpoint of operation of energy storage trains. Moreover the route Orunia Górna – Wrzeszcz – Osowa – Chylonia – Port Oksywie has been proposed, with alternating electrified and non-electrified sections. The initial calculations have been conducted.*

***Streszczenie:*** *Rozważono zastosowanie nowoczesnych zespołów trakcyjnych na liniach pasażerskich Trójmiasta. Zaproponowano budowę linii Gdańsk Śródmieście – Orunia Górna oraz odtworzenie komunikacji do północnych dzielnic Gdyni. Przeanalizowano trójmiejski układ komunikacyjny dla ruchu pociągów z zasobnikami energii. Zaproponowano trasę Orunia Górna – Wrzeszcz – Osowa – Chylonia – Port Oksywie z naprzemiennie występującymi odcinkami zelektryfikowanymi i niezelektryfikowanymi. Wykonano wstępne obliczenia.*

***Keywords:*** *train transportation, electric multiple unit, batteries, train line*

***Słowa kluczowe:*** *transport kolejowy, zespół trakcyjny, akumulatory, linia kolejowa*

*[1)] Three City – agglomeration of Gdansk, Sopot, Gdynia.*

## 1. INTRODUCTION

Nowadays, only Diesel-powered train vehicles operate in non-electrified train lines in Poland. The operation of these vehicles does not require advanced railway infrastructure; still, their impact on the local natural environment is negative owing to emission of harmful substances produced during combustion of Diesel oil. Moreover, multiple units are perceived as noisy and not dynamic enough.

Pomorska Kolej Metropolitalna (Pomeranian Metropolitan Railway, PKM) operates the route between Gdańsk Wrzeszcz and Port Lotniczy. This section is urban in character (short distances between stops) as well as mountainous, on account of numerous curves and gradients up to 27 ‰. It is planned to improve train dynamics over this route by replacing DMUs with standard EMUs (simultaneous electrification of the line is required). If passenger trains should return to section Gdynia Chylonia – Port Oksywie, then the cost of line electrification would be substantial. The construction of new transport connection (for instance to southern districts of Gdańsk) is considered only in the light of constructing traction network or possibly introducing DMUs.

The operation of the line by using traction vehicles with battery storage is an alternative to costly electrification of the line and environmentally-harmful operation of Diesel vehicles. The introduction of battery-powered vehicles does not demand the design and construction of traction network, which is characterized not only by high construction costs, but it also has a detrimental effect on the local landscape. This is particularly true in relation to PKM line, since in Gdańsk – Gdynia region it runs in the vicinity of Trójmiejski Park Krajobrazowy (Tricity Landscape Park).

Modern battery electric multiple units are as dynamic as standard electric vehicles. Breaks during operation are not required, since batteries are charged during runs over electrified sections of the line.

## 2. EVOLUTION OF ELECTRIC MULTIPLE UNITS WITH ENERGY STORAGE SYSTEMS

### 2.1. Earliest battery trains

The history of passenger battery-powered railway cars in Pomorze (Pomerania) region dates back to over one hundred years ago. In 1909 the Prussian railways started to operate 57 battery-powered units; these were called "Wittfeld" to honour the designer. Before WWI number of units in service increased to 171. Initially they were powered by lead-acid batteries, rated at 310 V and with capacity of 368 Ah (114 kWh). They were driven by two motors rated at 66 kW each, the unit mass ranged from 17 to 25 t and passenger capacity was 108, while unit speed was 50 km/h. During successive modernizations energy storage devices with capacity of 1088 Ah (610 kWh) and voltage equal to 560 V were installed. Then the train could run 300 km without additional battery charging [ 1]. Following the war, 20 of these units were used in Poland, 2 units were in service in Wolne Miasto Gdańsk (Free City of Danzig) [2]. In particular, they used to carry passengers over the route Gdańsk – Chojnice – Gdańsk without battery charging ( Fig.1a).

In 1926, Edison car went into service in New Zealand. It was equipped with NiFe battery, the range was 160 km and the maximum speed was equal to 48 km/h [3]. In 1932, Drumm battery train went into service in Ireland. It was powered with NiZn batteries and had a geared maximum design speed c. 80 km/h [4] with operating range 64 km. However, on account of low efficiency of old-time energy storage devices and long charging times, these vehicles were never batch-manufactured. Lithium-acid batteries with 1070 Ah capacity and 440 V voltage were used in 1958 in British cars with motor rating 2 x 100 kW [5]. Still, after less than 10 years, the line serviced by these trains was closed down. Another mass-produced battery railcar was manufactured in Germany, this was class ETA unit [5] operated by DB. The first variant of DB Class ETA 150 (Fig.1b) appeared in 1954, 232 motor cars were manufactured together with 216 trailer cars. The units were equipped with 2 motors of total power 300 kW and Lithium acid battery with capacity ranging from 352 kWh to 548 kWh in last car variant. With these batteries, trains were able to attain the speed of 100 km/h and operational range was 300 km. They remained in operation until 1995.

*a)*

*b)*

*Fig. 1. Battery-powered trains in 20th century: a) the only existing Wittfeld train, designation Ma 090 802 [2], b) battery-powered railcar, DB Class ETA 150 [5]*

### 2.2. Japanese unit series EV-E301 - a breakthrough in energy storage traction vehicles

The Japanese were the first in the world to introduce in railroading hybrid multiple units aiming at the limitation of negative impact of railway transport on natural environment [6]. In 2005 65% of Japanese tracks were electrified. The electrification of little-used lines proved to be unprofitable or technically difficult (e.g. low bridges). The most problematic lines were those connecting electrified regions to non-electrified regions, since it is not economical to run a vehicle, which does not utilize the traction network, over an electrified section of track. Since 2008 the Japanese worked on the prototype called "New Energy Train", abb. "NE Train". It had been previously used in the project of hybrid, i.e. Diesel-electric vehicle. They found that utilization of hybrid vehicles such as Battery Electric Multiple Unit (BEMU) will not only increase the effectiveness of transportation system and will lessen emission of $CO_2$ on the local scale, but will also reduce resources required for maintenance and service of these vehicles in relation to Diesel vehicles. After commissioning, a multiple unit called EV-E301 entered into commercial operation (Fig.2) [6]. The technical data of this unit is presented in Table 1. Operation of this unit started in 2014 over the route Utsunomiya – Karasuyama.

This line consists of two sections; the first one (Utsunomiya – Hoshakuji) is 11.7 km long and is electrified, with one stop present. The second section (Hoshakuji – Karasuyama ) is 20.4 km long with 6 stops and is not electrified.

Table 1. Technical data of battery electric multiple unit EV-E301 [6]

| | |
|---|---|
| Main circuit voltage | 630 V DC |
| Maximum speed | 100 km/h |
| Acceleration | 0.556 m/s$^2$ |
| Drive system | Three-phase and two-level DC/DC converter,<br>Three-phase and two-level DC/AC converter |
| Motors | 4 three-phase induction motors, rated at 95 kW each |
| Energy storage | Li-Ion batteries with total capacity 190 kWh |

*Fig. 2. Energy storage multiple unit EV-E301 [7]*

### 2.3. BEC819 electric multiple unit with energy storage supplied from AC traction network

The successful project EV-E301 was continued and expanded. BEC819 vehicle was built in order to ensure interoperability of electrified AC lines and non-electrified lines. BEC819 was designed and introduced basing on development work of concept multiple unit 817-1000 (the report appeared in 2015 paper [8] The authors modernized the existing electric multiple unit series 817, which was supplied from AC traction network 20 kV/60 Hz. The EMU series 817 was supplemented with batteries installed under the vehicle floor; in this way a concept unit series 817-1000 was born. This unit could run over electrified as well as over non-electrified lines. The technical data for EMU series 817-1000 is presented in Table 3. In 2016 BEMU BEC819 started its service over line Fukuhoku Yukata (electrified line, 20 kV AC) and Chikuho (no traction network), and then also it was used to operate Kashii line, replacing all Diesel multiple units (DMU) [10]. The twin design of BEC819 series vehicle is multiple unit EV-E801 series. The first EV-E801 trains started to run in 2017; they operated with 20 kV AC supply from traction network (Ou main line) and ran also over non-electrified Oga route [11]. In this way, JR East plans to replace all DMUs with BEMUs [9].

Table 2. Technical data of battery electric multiple unit 817-1000 [8]

| | |
|---|---|
| Axle arrangement | 2 cars (Mc-Tc) |
| Weight | Before modernization: 6322 t<br>After modernization: 67.1 t |
| Motors | 4 three-phase induction motors, rated at 150 kW each |
| Energy storagei | Li-Ion batteries, Mn type<br>1382 V, 83 kWh |

*Fig. 3. EMU with energy storage, BEC819 series [8]*

### 2.4. Dynamic development of EMUs with energy storage in European markets

First European tests of traction energy storage vehicle called IPEMU (Independently Powered Electric Multiple-Unit) were carried out in United Kingdom in 2015. This vehicle was constructed on the basis of electric unit Class 379 "Electrostar" manufactured by Bombardier and supplied from 25 kV/50 Hz network. This vehicle was equipped with Lithium Iron Magnesium Phosphate batteries facilitating its run over non-electrified parts of railway line. It was tested over a 15.1 km long track, between Harwich International Station and Manningtree Station [10].

In 2017 Stadler company presented a new vehicle called WINK (Fig. 4a); 18 trains were ordered by Dutch operator Arriva Netherlands. WINK is a two-car multiple unit train, dedicated for running over secondary lines with inconsiderable number of passengers and numerous stops. This vehicle is distinguished by high flexibility of drive system, which may be configured in three different ways. The first one, a standard HP Diesel engine is used, fed with Diesel oil or hydrotreated vegetable oil (HVO). The second one, a hybrid drive may be used, consisting of Diesel engine and traction supply system. The third one, traction supply and batteries are combined to create the most environmentally-friendly drive system. WINK trains will run in northern part of the Netherlands over route Leeuwarden-Groningen, as well as in Frisia and Groningen provinces. A partial electrification of Leeuwarden – Groningen route is planned. There, vehicle batteries with total capacity of 748 kWh will be charged and then used to power the vehicle running over non-electrified part of line. All 18 vehicles should be delivered by the end of 2020 [11,12].

The second Stadler train with energy storage is Flirt Akku (Fig. 4b) was presented in 2018. It was designed on the basis on Flirt all-electric model supplemented with batteries facilitating use of train over non-electrified sections of track. This train may run for 80 km using batteries only. Maximum speed of Flirt Akku train is 140 km/h. Full battery charging takes 15-20 minutes [11]. In 2019 Stadler company was awarded a contract for delivery of 55 Flirt Akku multiple units to Schleswig – Holstein Land in northern Germany. These units will operate e.g. on non-electrified route Kiel – Lübeck. German media state that delivery of all vehicles should be completed by 2022 [12].

*a)*

*b)*


*Fig.4.. a) EMU with energy storage Stadler WINK [11], b) EMU with energy storage Stadler Flirt Akku [11]*

In 2018, Siemens Mobility and Austrian State Railways (ÖBB) presented a new traction vehicle called Desiro ML Cityjet Eco (Fig. 5a). It was developed under the auspices of Austrian project aimed at complete elimination of DMUs from national rolling stock by 2035. On electrified lines, the units may be supplied from traction network 15 kV or 25 kV. On non-electrified lines the train is supplied from Lithium Titabate batteries with 528 kWh capacity [12]. The unit is driven by 4 induction motors of 2600 kW total power, which allows maximum speed of 140 km/h [13]. By January 2020, tests in passenger operation were started on railway lines near Vienna. They lasted for two months and were planned as the final stage before putting the trains into commercial service [14].

*Fig. 5. EMU with energy storage Siemens Desiro ML Eco [13],*

Among the newest designs of energy storage multiple units, we find Coradia Continental model manufactured by Alstom company, with battery-electric supply (Fig.6). This is a modified standard electric multiple unit (with catenary supply). The modification is based upon positioning high-voltage Li-Ion batteries on the vehicle roof. According to

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

the manufacturer, these batteries should allow battery-powered operating range of 120 km and maximum speed should be 160 km/h. A contract for delivery of 11 Coradia Continental BEMUs was signed in February 2020. These trains will run on non-electrified 80 km long railway line between Chemnitz and Leipzig. New units should be commissioned in 2023 [15].

*Fig. 6. Alstom Coradia Continental BEMU [15]*

## 3. DETAILED DESCRIPTION OF PROPOSED LINE ORUNIA GÓRNA - GDAŃSK ŚRÓDMIEŚCIE - GDAŃSK WRZESZCZ - PORT LOTNICZY - OSOWA - GDYNIA CHYLONIA - PORT OKSYWIE

To assess the advisability of employing IPEMUs, we propose to analyse a route consisting of alternately electrified and non-electrified sections – Fig. 6. The route starts with hitherto non-existing section between Orunia Górna and Gdańsk Śródmieście. Then the route runs over line 250 to railway station Gdańsk Wrzeszcz, afterwards it turns to line 248 in the direction of the Port Lotniczy and Osowa. Then it runs over line 201 from Osowa do Gdynia Główna. From Gdynia Główna line 250 runs to Gdynia Chylonia, and then it joins line 723 up to Gdynia Port Centralny. By Gdynia Rzeźnia the route joins line 228 connecting Rumia and Gdynia Port Oksywie (where the route is terminated).

The route consists of electrified sections (i.e. with traction network) and non-electrified sections, where the train might be driven with Diesel engine or, in the case of an electric vehicle, it might use on-board energy storage. Electrification status of different sections is enumerated below:

A. **Orunia Górna – Gdańsk Śródmieście** – section non-existent so far, in concept phase, it may remain non-electrified,

B. **Gdańsk Śródmieście – Gdańsk Wrzeszcz** – electrified,

C. **Gdańsk Wrzeszcz – Gdańsk Port Lotniczy – Osowa** – non-electrified, electrification is planned,

D. **Gdańsk Osowa – Gdynia Główna** – electrification is planned,

E. **Gdynia Główna – Gdynia Chylonia** – electrified,

F. **Gdynia Chylonia – Gdynia Port Oksywie** – non-electrified, to be revitalised.

It is assumed that line 201 (Nowa Wieś Wielka - Gdynia Port) will be electrified on account of its importance in freight operations and a second track will be added in the near future. That is why we consider that D section is electrified. The point where electrification should begin after stop at Gdańsk Port Lotniczy is under consideration. This may be a place behind the exit from the overpass and located behind the air terminal, where train depot is, or at Gdańsk Rębiechowo stop or even at Osowa railway station.

Discussion of sections devoid of traction network (A,C,F) is provided in subsequent chapters. These sections would be used by electric vehicles utilizing energy stored in on-board storage facilities. The simulation runs presented in Chapter 4 have also been calculated based on identical route sections.


*Fig. 7. The railway route under consideration: Orunia Górna – Port Oksywie; sections without traction network are marked in green*

### 3.1. Orunia Górna - Gdańsk - Śródmieście (section A)

The city authorities have been planning a route running to southern city districts of Gdańsk for the last 20 years. Lately, the idea surfaced again and the concept of constructing SKM (fast suburban railway) line to Orunia Górna station was presented. On the basis of media information, we find that several different routes are taken into account. Here we shall discuss the route starting in Gdańsk Śródmieście – see Fig. 7 [16 – 18]. The initial point on the map (marked in green) is the train stop Gdańsk Śródmieście, while the end point is current tram terminal Łostowice. At this location the last station of first construction stage is planned.

Some of present-day tracks might be used (those utilized by SKM): the line from Gdańsk Śródmieście stop would be constructed with overpass over Trakt Św. Wojciecha and Radunia Canal.

Ahead, some barren lands are found, slightly more elevated than Małomiejska Street, so some excavations would prove necessary. Afterwards line would run to Ptasia Street and there another overpass is planned. Since Ptasia Street lies lower than preceding barren lands, this fact might be utilized and tracks would be laid down without increasing slope of the route. Then the route would run parallel to Małomiejska Street down to the tram terminal

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

Łostowice. This fragment of the route would be furnished with three railway stops: Gdańsk Południe, Stare Szkoty and Łostowice-Świętokrzyska. It is also planned to make the connection to tram terminal and to create a transport hub (railway, tram, bus stops).

To meet the requirements of energy calculations in Wikiloc programme, the profile of the route between Orunia Górna and Gdańsk Śródmieście has been determined and afterwards this was theoretically smoothed down. The original (true) profile is shown in Fig. 9 (blue line) as well as the smoothened profile (red line).

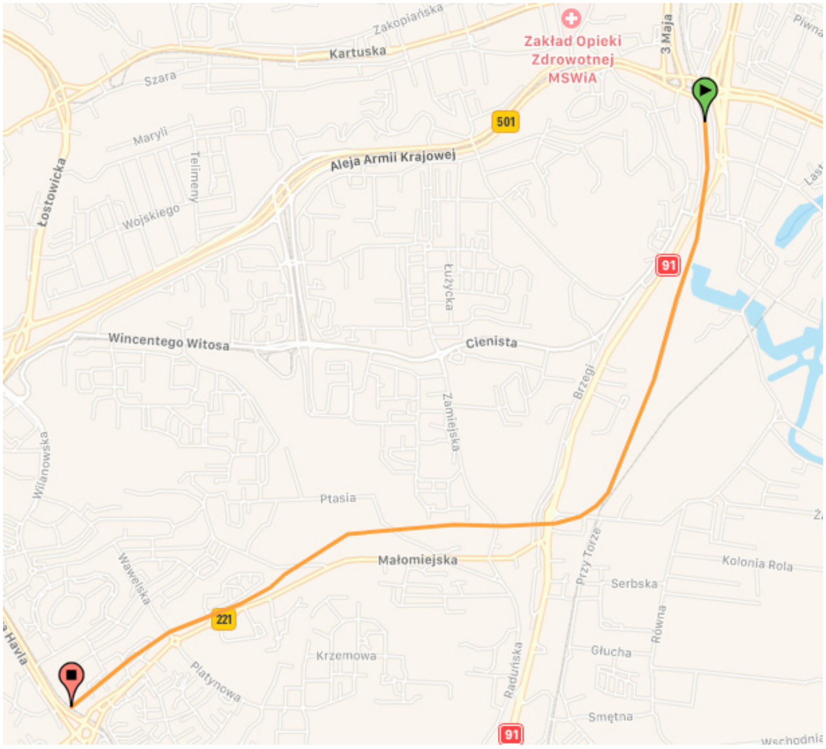



*Fig. 8. Railway route to Orunia Górna*

From Gdańsk Południe stop the route will run through overpass over Trakt Św. Wojciecha. Therefore, at location 1.5 km away from Gdańsk Śródmieście stop, a slope has been introduced (somewhat analogous to the overpass in PKM line in the neighbourhood of SKM stop Gdańsk Zaspa). Another overpass is planned over Ptasia Street – see profile. When Radunia Canal is passed (2 km down), the land is considerably elevated in relation to adjacent Małomiejska Street, hence excavations will be necessary.

The planned locations of stations relative to departure station (in both directions) are given in Table 4. The calculated slopes along the route are presented in Table 5. The different slopes do not exceed slopes existing in section of PKM line between PKM Wrzeszcz and Port Lotniczy. In this initial discussion, curves of the track and the resulting horizontal profile have been neglected.

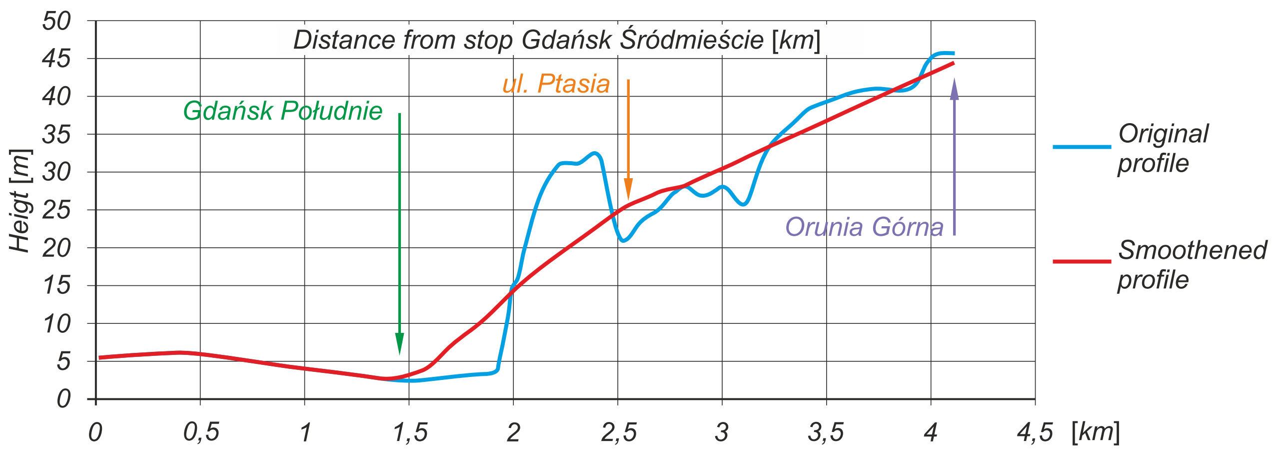



*Fig. 9. The profile of planned line Gdańsk Śródmieście – Orunia*

Table 4. Locations of train stations along railway route

| Route Śródmieście – Łostowice | | Route Łostowice – Śródmieście | |
|---|---|---|---|
| Name of stop | distance s [km] | Name of stop | distance s [km] |
| Śródmieście | 0.00 | Łostowice | 0.00 |
| Południe | 1.42 | Stare Szkoty | 1.85 |
| Stare Szkoty | 2.32 | Południe | 2.76 |
| Łostowice | 4.17 | Śródmieście | 4.17 |

Table 5. Slopes of train route Gdańsk Śródmieście – Gdańsk Orunia Górna

| Distance from Gd. Śródmieście [m] | Slope [‰] |
|---|---|
| 0 – 300 | 1.6 |
| 300 – 400 | 2.6 |
| 400 – 500 | 0.6 |
| 500 – 600 | -3.3 |
| 600 – 700 | -2.3 |
| 700 – 800 | -3.9 |
| 800 – 1000 | -4.5 |
| 1000 – 1300 | -3.3 |
| 1300 – 1575 | -3.5 |
| 1575 – 1670 | 8.57 |
| 1670 – 1715 | 26.3 |
| 1715 – 1850 | 20 |
| 1850 – 2000 | 24.44 |
| 2000 – 2100 | 7.6 |
| 2100 – 2600 | 20.6 |
| 2600 – 2800 | 12 |
| 2800 – 2900 | 7 |
| 2900 – 4100 | 12.71 |

### 3.2. Gdańsk Wrzeszcz - Port Lotniczy (section C)

Among the non-electrified sections, the route Gdańsk Wrzeszcz – Port Lotniczy proves most demanding from the energy viewpoint on account of steep gradients. There are eight stops along the route, their distances from the departure station are presented in Table 6 [20, 21]. Nowadays, this route along with its extension to Kartuzy/Kościerzyna and Gdynia is maintained by two operators and DMUs are used.

Table 6. Locations of train stations along railway route Wrzeszcz – Port Lotniczy

| Wrzeszcz – Port Lotniczy | | Port Lotniczy – Wrzeszcz | |
|---|---|---|---|
| Name of stop | distance – s [km] | Name of stop | distance – s [km] |
| Wrzeszcz | 0.00 | Port Lotniczy | 0.00 |
| Strzyża | 2.31 | Matarnia | 2.98 |
| Niedźwiednik | 3.95 | Kiełpinek | 5.79 |
| Brętowo | 5.40 | Jasień | 7.27 |
| Jasień | 7.50 | Brętowo | 9.36 |
| Kiełpinek | 8.98 | Niedźwiednik | 10.81 |
| Matarnia | 11.78 | Strzyża | 12.45 |
| Port Lotniczy | 14.76 | Wrzeszcz | 14.76 |

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

### 3.3. Gdynia Chylonia - Port Oksywie (section F)

The route from Gdynia Chylonia to Port Oksywie consists of six stops, their distances from the departure station are shown in Table 7. The electrified section in line 723 is used by freight trains. The non-electrified section is currently out of service and it requires modernization of platforms at stops. New constructions improving transport capacity are planned along this route (overpass in Pucka Street; the work should start in 2021 [32]).

Table 7. Locations of train stations along railway route Chylonia – Port Oksywie

| Chylonia – Port Oksywie | | Port Oksywie – Chylonia | |
|---|---|---|---|
| Name of stop | distance – s [km] | Name of stop | distance – s [km] |
| Chylonia | 0.00 | Port Oksywie | 0.00 |
| Rzeźnia | 2.55 | Obłuże | 1.67 |
| Pogórze | 3.83 | Obłuże Leśne | 2.73 |
| Obłuże Leśne | 5.09 | Pogórze | 3.99 |
| Obłuże | 6.15 | Rzeźnia | 5.27 |
| Port Oksywie | 7.82 | Chylonia | 7.82 |

## 4. CALCULATIONS OF TRAIN PERFORMANCE OVER NON-ELECTRIFIED SECTIONS

A simulation run is carried out in order to analyse instantaneous and total energy consumption of the vehicle. These values form the basis for calculating drive and supply system parameters. We have analysed a run of a vehicle with and without energy storage device (with energy storage present, vehicle mass is increased by battery mass). The calculations of simulation run are based on equations of motion and assumptions such as train mass, maximum speed, set acceleration at start-up and possibly deceleration during recuperation braking.

The fundamental quantities adopted in calculations of simulation run are as follows:

- tractive effort (nett force vs. speed) curve of the vehicle and corresponding supply current vs. speed curve,
- braking force vs. speed curve,
- route profile.

These quantities are set in accordance with technical data of the train and route profile.

### 4.1. Tractive effort of a given electric multiple unit

In further discussion, we have considered a batch-manufactured electric multiple unit. In theory, this might be supplemented by energy storage. Taking into account steep gradients at some points along the route, we adopted a two-car unit with relatively low mass (without load – data is provided in Table 8. We have assumed that the train is fitted with a cruise control system, so that after start-up phase speed may be kept constant regardless of resistance to motion. The value of speed was set depending on the length of a section between stops: 80 km/h for the longest sections, 70 km/h for shorter sections and 60 km/h for the shortest sections.

Table 8. Selected parameters of Elf 34WE EMU Pesa; it is assumed that it might be equipped with energy storage

| | |
|---|---|
| Total length | 42 650 mm |
| Seating capacity | 113 |
| Maximum speed | 160 km/h |
| Number of motors, rated power | 4 x 400 kW |
| Acceleration during start-up | 1,3 $m/s^2$ |
| Deceleration during braking | 1 $m/s^2$ |
| Total mass | 83.2 tons |

The tractive effort curves for braking and start-up have been determined. The first part of the curve shows drive operating in constant torque zone (constant force), i.e. during start-up and braking. The second part relates to constant power operation. The curve is shown in Fig. 9.

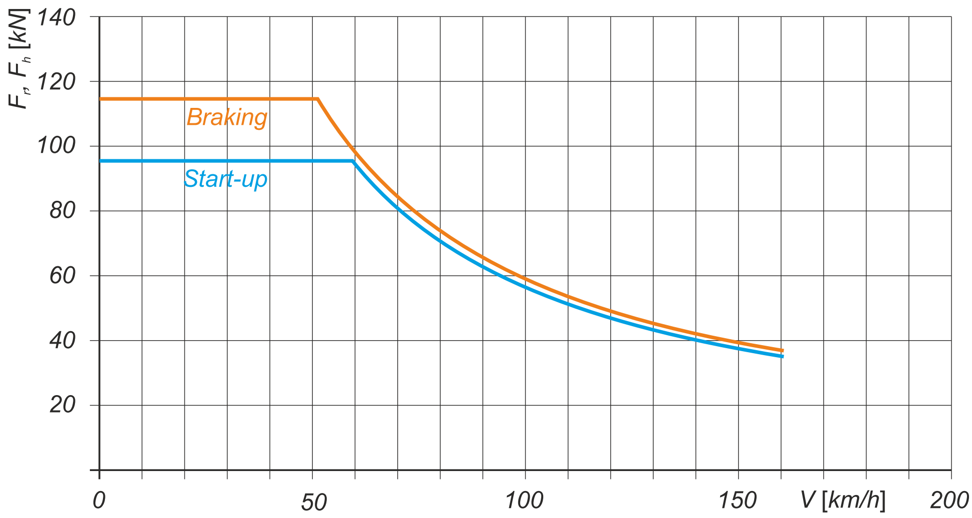



*Fig. 10 Tractive effort curve for Elf 34WE EMU by Pesa*

### 4.2. Calculations of train performance

Simulation run calculations are initialized with basic relationship of tractive effort, total resistance to motion and kinetic energy of vehicle versus distance [23]:

$$(F - W)ds = dE_k, \tag{1}$$

where:

$F$ [N] – tractive effort of the train, instantaneous value,
$W$ [N] – total resistance to motion, instantaneous value,
$s$ [m] – distance,
$E_k$ [J] – kinetic energy of the vehicle.

The following formula should be used to calculate kinetic energy:

$$E_k = \frac{m \cdot k \cdot v^2}{2}, \tag{2}$$

where:

$m$ [kg] – vehicle mass ,
$k$ – rotary allowance,
$v$ – vehicle speed.

When (2) is substituted into (1), we obtain a relationship:

$$\frac{dv}{ds} = \frac{F - W}{m \cdot k \cdot v}. \tag{3}$$

And by representing speed as distance covered over time, we obtain equation for dynamics of motion:

$$\frac{dv}{dt} = \frac{F(v) - W(v,s)}{m \cdot k}. \tag{4}$$

To find coefficients of formula (4), we need to determine train's total resistance to motion. This resistance may be divided into rolling resistance and additional ("local") resistance. The "local" resistance relates to route profile, while rolling resistance is related to aerodynamic forces and is usually expressed with the help of empirical formulas. In the case of Polish EMUs, the rolling resistance may be formulated as [22]:

$$W_z = (0,65 + 0,054 \cdot v) \cdot Q_z + 147 \cdot n_{oz} + (2,7 + n_w) \cdot 1,271 \cdot v^2, \tag{5}$$

where:

$W_z$ [N] – rolling resistance to motion ,
$Q_z$ [kN] – axle load,
$n_{oz}$ – number of axles in EMU,
$n_w$ – number of cars in EMU.

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

Grade resistance to motion is expressed by formula:

$$W_i = Q_z \cdot i \quad , \tag{6}$$

where:
$W_i$ [N] – grade resistance to motion,
$i$ [‰] – resultant slope of route.

So, instantaneous value of accelerating force is calculated as:

$$F_a = F(v) - W(s,v) = F_p - W_i - W_z \quad . \tag{7}$$

Relationship between time increment and distance is determined by formula:

$$\Delta t = \frac{\Delta v}{\frac{F(v) - W(v,s)}{m \cdot k}} \quad , \tag{8}$$

where
$\Delta t$ [s] – time increment
$\Delta v$ [m/s] – speed increment,
$a$ [m/s$^2$] – acceleration.

Distance covered in time is calculated in a following way:

$$\Delta s = v_{śr} \cdot \Delta t \quad , \tag{9}$$

where:
$\Delta s$ [m] – distance increment ,
$V_{śr}$ [m/s] – average speed .

In calculating travelling time between stations, 30-second stops were assumed. The results of simulation run over three non-electrified sections in both directions are shown below.

The maximum speed of 70 km/h was adopted for section Gdańsk Śródmieście – Łostowice on account of high grades and small distances between stations. The course of speed versus distance over route Gdańsk Śródmieście – Gdańsk Łostowice is shown in Fig. 10 (the course for return route is the same). The course of speed versus distance over route Gdańsk-Śródmieście – Gdańsk Łostowice is shown in Fig. 11.

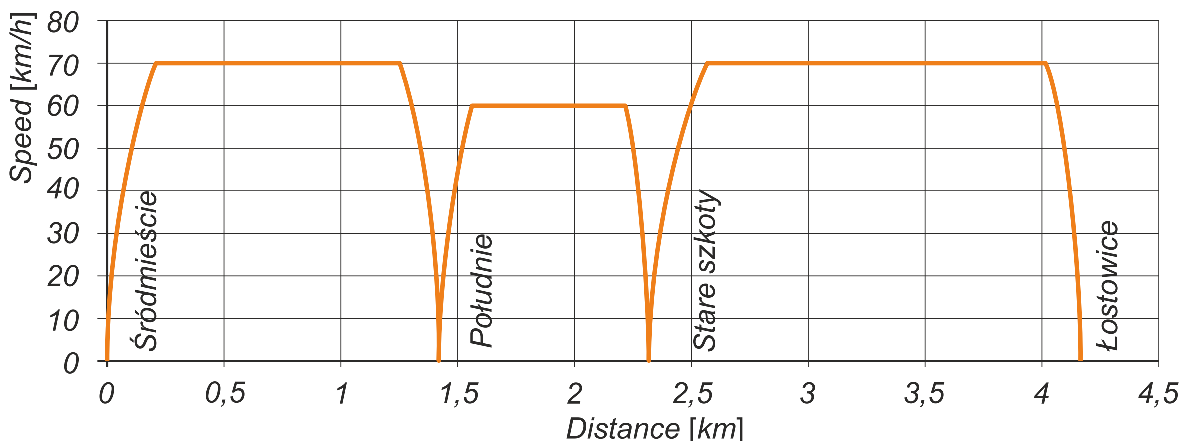



*Fig. 11. Speed vs. distance for Gd. Śródmieście – Gdańsk Łostowice train route*

For section Wrzeszcz – Port Lotniczy the total travelling time was 17.58 minutes, while the return travel took 17 minutes. The journey time between Wrzeszcz – Port Lotniczy is longer on account of a slope. The maximum grade along this route is 27‰, so the route is classified as mountainous. The course of speed versus distance is shown in Fig. 12 (the return course is similar). The calculated course of distance versus time for route Gdańsk Wrzeszcz – Gdańsk Port Lotniczy has been shown in Fig. 13.

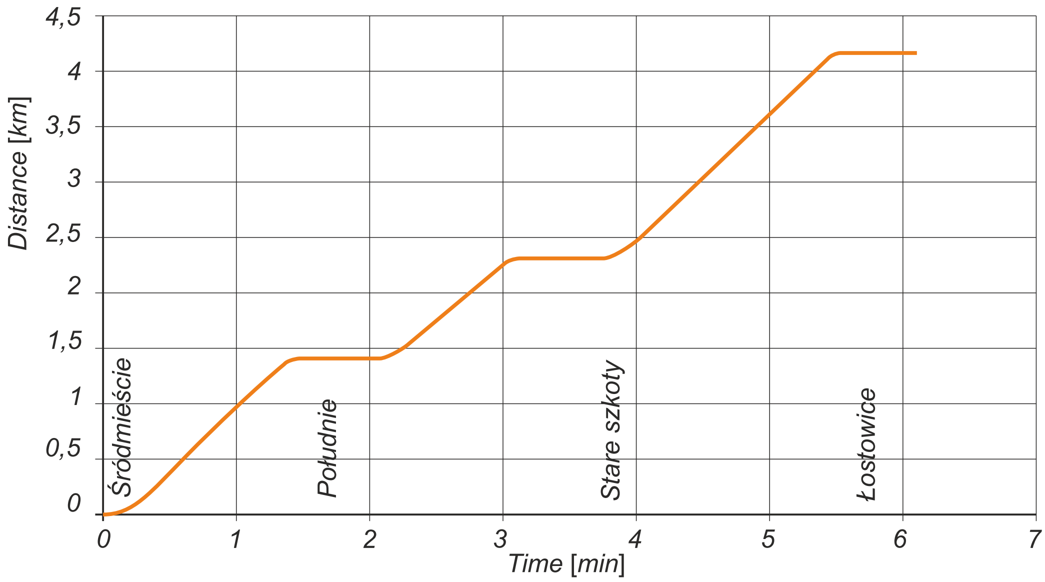



Fig. 12. Speed vs. distance for Gd. Śródmieście – Gdańsk Łostowice train route

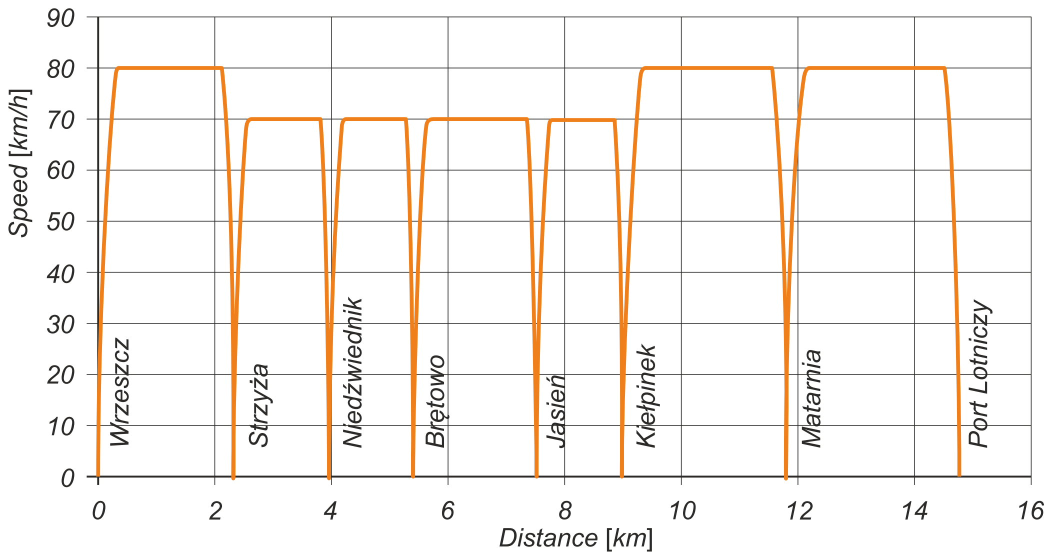



Fig. 13. Speed vs. distance for Gdańsk Wrzeszcz – Gdańsk Port Lotniczy train route

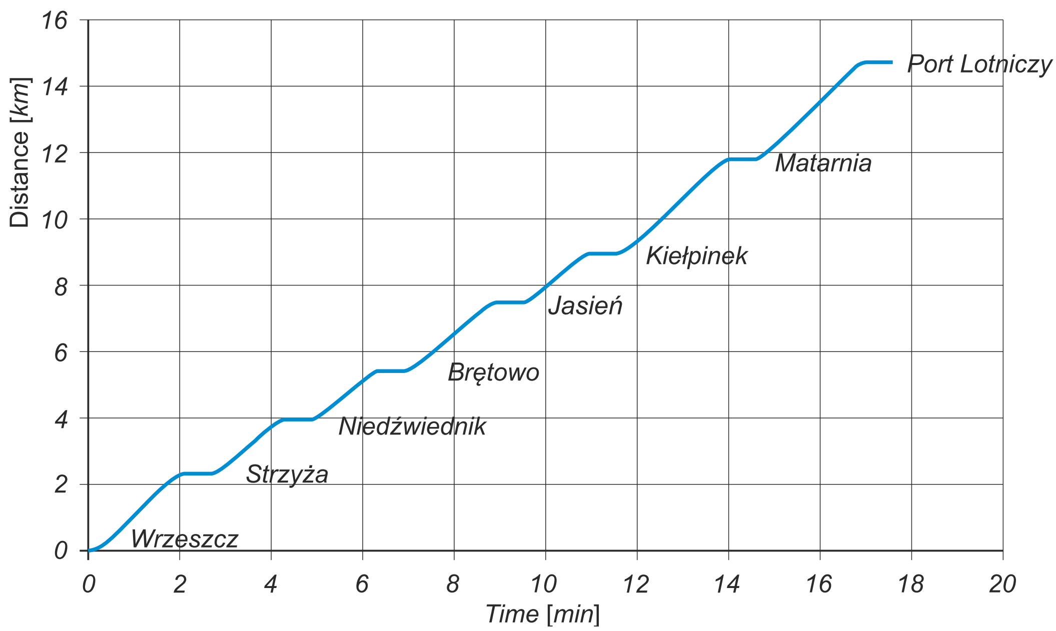



Fig. 14. Distance vs. time for Gdańsk Wrzeszcz – Gdańsk Port Lotniczy train route

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

The journey between Port Oksywie and Gdynia Chylonia lasts for 10.48 minutes according to our calculations, and the return route takes 10.5 minutes. The length of this track section is 7.818 km. In this section the grades are the smallest in relation to non-electrified sections analysed previously. The course of speed versus distance for route Gdynia Chylonia – Port Oksywie is shown in Fig. 14. The return course is almost the same. The calculated course of distance versus time for route Gdynia Chylonia – Gdynia Port Oksywie is shown in Fig. 14.

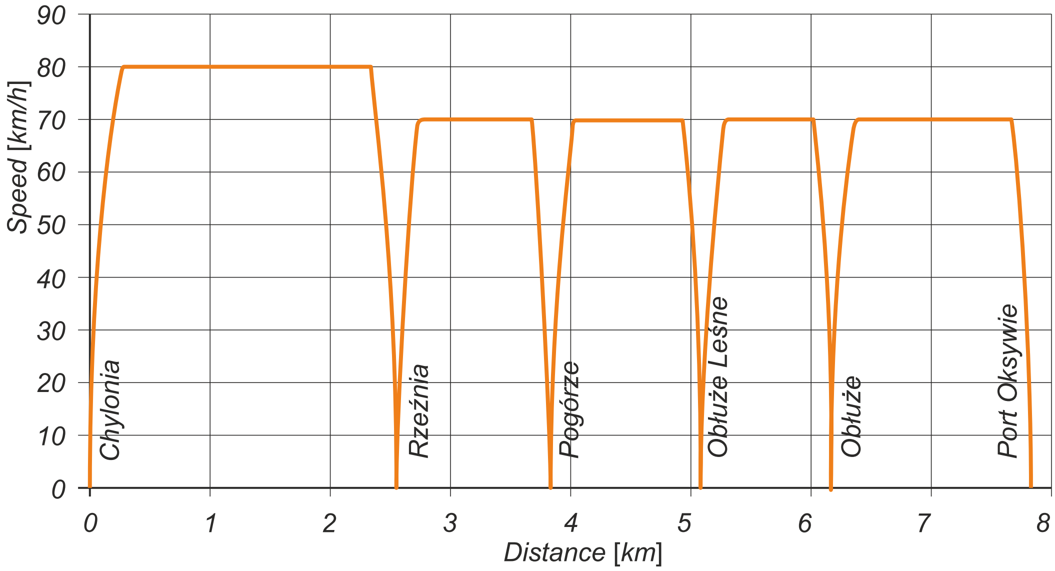
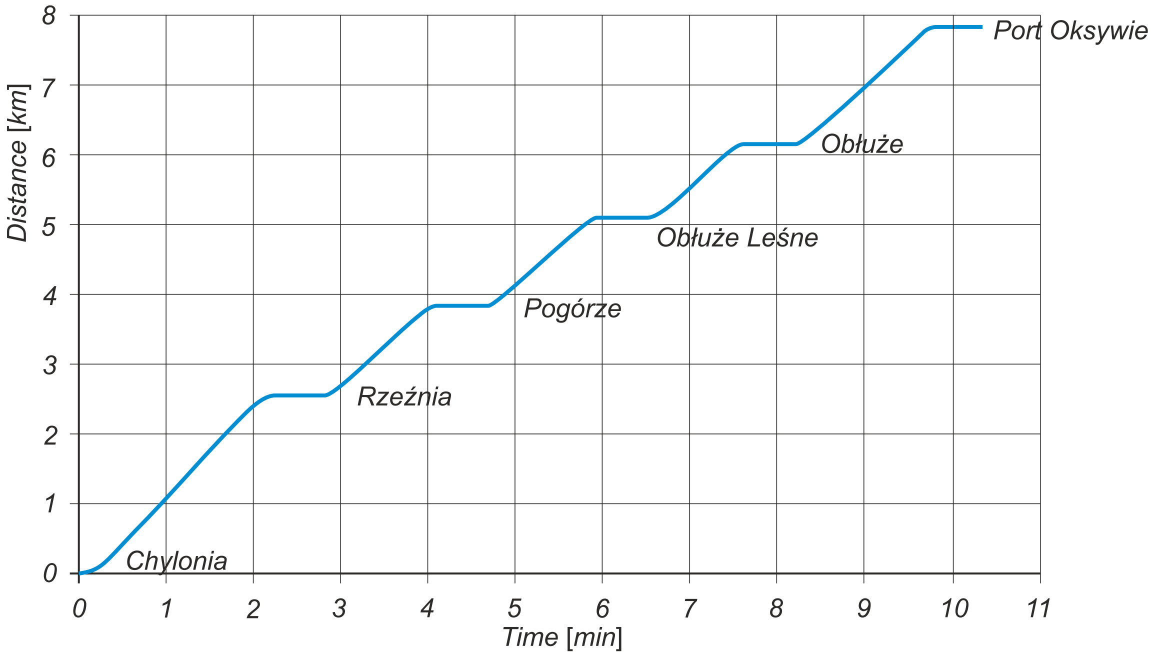



Fig. 15. Speed vs. distance for Gdynia Chylonia – Gdynia Port Oksywie train route




Rys. 16. Distance vs. time for Gdynia Chylonia – Gdynia Port Oksywie train route

The simulations constitute the basis for calculating vehicle's energy demand for battery-powered runs. This issue will be presented in our next paper entitled Battery electric multiple units running over partially electrified route Orunia Górna – Osowa – Port Oksywie.

## 5. CONCLUSIONS

The history of passenger battery-powered trains in Pomorze (with operating range up to 300 km) should provoke the discussion on the advisability of introducing similar designs on the new non-electrified lines instead of undertaking expensive construction and maintenance of traction network (which is debatable from an aesthetic point of view as well). The said vehicles operated in Kokoszki Railway; most tracks of this Railway within Gdańsk boundaries are utilized by present PKM (Pomeranian Metropolitan Railway) and DMUs are mostly used here. The inference is that battery-powered cars were able to cope with the curves and grades in this route.

In the beginning of the 21st century, the leading role in the technology of energy-storage trains was played by the Japanese. Their trains were used on partially-electrified lines. The dynamic development of European battery-powered vehicles was launched with the British tests of Independently Powered Electric Multiple-Unit (IPEMU) in 2015. In 2017 different BEMUs were commissioned into use for non-electrified lines in the Netherlands, Germany and Austria. The operational ranges of these units are much smaller than those of vehicles from over a century ago, since it is assumed that they will be used on partially-electrified lines.

The presented discussion shows that we have a unique opportunity of reconsidering electrification of three newly-constructed (PKM) and several planned train lines in Three City. Passenger transportation along the route consisting of alternately electrified and non-electrified sections Gdańsk Orunia Górna – Śródmieście – Wrzeszcz – Port Lotniczy – Osowa – Gdynia Głównia – Gdynia Chylonia – Port Oksywie could be carried out with IPEMUs. The power calculations commenced in the current paper will be continued, and the results presented in the subsequent paper will prove that it is possible to introduce battery-powered trains to Three City and that they will run successfully with batteries charged fully over electrified sections of the route. Pomorze Gdańskie (Pomerelia region) may become a forerunner of modern battery electric multiple units in Poland, while at the same time the needless electrification of lines may be avoided and unique landscape could be protected.

## BIBLIOGRAPHY

[1] "Akumulatorowy zespół trakcyjny Ma 090802 typu Wittfeld". psmk.org.pl (data dostępu 28.11.2020 r.)

[2] "Akumulatorowe wagony motorowe typu Wittfeld". archeo.kolej.pl (data dostępu 28.11.2020 r.) Fot. Paweł Mierosławski, 1996

[3] Edison Storage Battery Rail Car. –" Successful In Catenbury District. The New Zealand Electronic Text Collection". nzetc.victoria.ac.nz (data dostępu 21.11.2020 r.)

[4] H. Oram. "An Irishman's Diary". irishtimes.com (data dostępu 21.11.2020 )

[5] DB Akkutriebwagen ETA/ESA 150(ab 1968 515/815):finemodels.de/in-auslieferung/db-eta-esa-150.de (data dostępu 1.12.2020)

[6] N. Shiraki, K. Tokito, R. Yokozutsumi. "Propulsion system for catenary and storage battery hybrid electric railcar series EV-E301" 2015 International Conference on Electrical Systems for Aircraft, Railway, S*hip Propulsion and Road Vehicles (ESARS)*, Tokio, Japonia 2015.

[7] Y. Taguchi, S. Kadowski, T.,Nakamura, M. Miki, K. Hatakeda, Y. Arita. "Development of a Traction Circuit for Battery-powered and AC-fed Dual Source EMU and Running Test Evaluation of the On-board Battery Performance". *Quarterly Report of RTRI* 56(2): 98-104, Maj 2015.

[8] Japanese Railway Information No.136, Series BEC819 „DENCHA" Battery-powered Train Charged from AC Overhead Lines", Tokio, Japonia 2016.

[9] trafficnews.jp, JR Kyushu will replace the Kashii Line trains with BEC819 trains "DENCHA", https://trafficnews.jp/post/82377 (data dostępu 19.02.2020)

[10] railway-technology.com, Independently Powered Electric Multiple-Unit (IPEMU), Essex, https://www.railway-technology.com/projects/independently-powered-electric-multiple-unit-ipemu-essex/, (data dostępu 20.02.2020 )

[11] rynek-kolejowy.pl, Debiut Flirta Akku. Do 80 kilometrów bez sieci trakcyjnej, https://www.rynek-kolejowy.pl/mobile/tylko-u-nas-debiut-flirta-akku-do-80-kilometrow-bez-sieci-trakcyjnej-88700.html, (data dostępu 21.02.2020 )

[12] rynek-kolejowy.pl, Stadler zdobędzie zamówienie na 55 Flirtów Akku dla Szlezwiku-Holsztynu, https://www.rynek-kolejowy.pl/wiadomosci/stadler-zdobedzie-zamowienie-na-55-flirtow-akku-dla-szlezwikuholsztynu-92446.html, (data dostępu 21.02.2020 )

[13] railway-technology.com, Desiro ML Cityjet eco Passenger Train, https://www.railway-technology.com/projects/desiro-ml-cityjet-eco-passenger-train/, (data dostępu 22.02.2020 )

[14] assets.new.siemens.com, Desiro ML ÖBB Cityjet eco for ÖBB Personenverkehr AG, https://assets.new.siemens.com/siemens/assets/api/uuid:b26911b1-2b0e-48b4-b593-81adbf032d75/db-desiro-ml-oebb-cityjet-eco-e.pdf, (data dostępu 22.02.2020 )

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149

[15]alstom.com, Alstom signs first contract for battery-electric regional trains in Germany, https://www.alstom.com/press-releases-news/2020/2/alstom-signs-first-contract-battery-electric-regional-trains-germany, (data dostępu 24.02.2020)

[16] M. Stąporek. "Wizja SKM na południe Gdańska. Na ile realna?" https://www.trojmiasto.pl, (data dostępu 7.04.2020)

[17]S. Zięba. "Krok w stronę wydłużenia SKM na południe Gdańska", https://www.trojmiasto.pl, (data dostępu 7.04.2020)

[18]K. Koprowski. "Którędy pojadą pociągi SKM przez Południe?" Propozycja naszego czytelnika. https://www.trojmiasto.pl, (data dostępu 7.04.2020).

[19]N. Karkosińska-Brzozowska, K. Karwowski. "Elektryczne autonomiczne jednostki trakcyjne na linii Pomorskiej Kolei Metropolitalnej?" T*echnika transportu szynowego* nr 12, 2015, s. 2638 - 2643

[20]N. Karkosińska-Brzozowska. "Możliwości zastosowania zasobnikowych jednostek trakcyjnych na liniach kolejowych na przykładzie Pomorskiej Kolei Metropolitalnej", *Problemy Kolejnictwa* vol. 50, nr 172, 2016, s. 19-24

[21]A. Jakubowski, N.,Karkosińska-Brzozowska, K. Karwowski, A. Wilk. "Storage electric multiple units on partially electrified suburban railway lines", *Przegląd Elektrotechniczny* nr 4, 2020, s. 158 - 161

[22]J. Bliński, M. Błażejewski, M. Malczewska, M.Szczepiórkowska. "Opory ruchu pojazdów trakcyjnych", *Technika Transportu Szynowego*, 3/2019.

[23]M. Bartłomiejczyk, L. Jarzębowicz, S. Judek, N. Karkosińska-Brzozowska, K. Karwowski, M. Mizan, J. Skibicki, A. Wilk. "Energetyka transportu zelektryfikowanego. Poradnik inżyniera", *Wydawnictwo Politechniki Gdańskiej*, 2018.

*otrzymano / received: 20.11.2020* *przyjęto do publikacji / accepted: 20.12.2020*

AUTOMATYKA – ELEKTRYKA – ZAKŁÓCENIA
Vol. 11, No 4 (42) 2020, December, ISSN 2082-4149