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Modern infrastructure and rolling stock solutions in the agglomeration rail transport on the example of the Line 2 of the Warsaw Metro

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Summary
The extension of the second line of the Warsaw Metro (M2), running from east to west, is currently under construction. The opening of sections in the eastern and western parts of the line has been carried out in 4 stages, successively handing over sections of 2–3 stations each. The section currently under construction is the last section of the 2nd line in the south western part, which also includes the construction of the Karolin technical and holding station (STP Karolin). The Varsovia trains delivered by Škoda, whose styling is similar to the Inspiro trains from Siemens, which have been in service on the Warsaw metro for several years, have been acquired for the rolling stock of the line. The construction of the metro was disrupted by the SARS-Cov-2 coronavirus pandemic (2020–2022) as, alongside a delay in the completion date or the delivery of rolling stock, it caused an increase in the price of materials and labor costs, forcing the parties (City Hall of Warsaw, contractors) to revalue the contract.

Keywords: metro, Warsaw, second line, Škoda

1. Introduction

The increasing number of inhabitants in the individual metropolitan areas makes it crucial to choose which means of public transport to resolve in order to make passenger transport efficient. Due to the promotion of ecological transport by the EU, public transport should use electrically powered vehicles, possibly driven by an electric motor. Furthermore, bus transport, although flexible (using virtually only the already existing road infrastructure), is currently in retreat due to the use of fossil fuel engines (EU policy does not provide for subsidies for the purchase of combustion vehicles). Thus, at present, the development of:

- trams,
- electric buses,
- trolleybuses,
- metros,
- suspension railway (monorail) or magnetic levitation railway,
- the urban railway is being promoted.

Each of the solutions has advantages and disadvantages, with the choice depending on the number of passengers to be transported in a predefined unit of time, as well as the available financial resources (table 1).

Tram transport is characterised by a relatively high degree of simplicity – the construction of the infrastructure is neither complicated nor costly, nor is the construction of the rolling stock (Fig. 1). Although further technical solutions are currently being implemented (e.g. accumulator batteries in vehicles, APS power supply, etc.), the essence of the aforementioned mean of transport remains inexpensive and uncomplicated, which has conditioned its high prevalence worldwide. The advantage of tram transport over bus transport is a greater transport capacity, which is of great importance in the towns with historical (narrow) buildings in the centre and the inability to develop bus transport due to limited street capacity (case of Cracow). The disadvantage is the much higher purchase cost of the vehicles (> 5–6 times), and this is not even compensated for by their much longer operating time (2–3 times).

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Table 1

Comparison of the different means of public transport means of public transport employing electric propulsion

Mean of transport	Advantages	Disadvantages	Cost of construction and operation	Transport capacity	Prevalence
Tram	relatively high transport capacity, including in towns with historic buildings (narrow streets), independence from road infrastructure	necessity to build the infrastructure, including the overhead contact lines	low	average	high
Trolleybus	lower costs of infrastructure construction compared to trams	necessity to suspend the overhead contact line and dependence on the road infrastructure	low	low	high
Electric bus	equipping vehicles with accumulator batteries eliminates the need to hang up the overhead contact line	high cost of purchasing vehicles	average	low	small
Metro	high transport capacity	high cost of infrastructure construction	high	large	limited to large or very large urban centres
Suspension railway (monorail) / magnetic levitation railway	small spatial needs for the construction of infrastructure	non-standard technical solutions require a relatively high technical culture	average	from low up to average	small
Urban railway (conventional)	possibility of using the existing railway infrastructure	considerable distance between stops (> 2–3 km), dependence on the railway infrastructure	average	high	average

[Own elaboration].

Fig. 1 The Hyundai Rotem 140N tram no. 4218, al. Jana Pawła II (18/03/2023) [photo: M. Graff]

Electric buses can be regarded as a variant of the accumulator battery-equipped trolleybus, therefore not requiring the construction of an overhead contact line, which also enables a flexible line design that lacks in the case of trolleybuses or trams (Fig. 2 and 3). The development of electric buses falls in the last 10–15 years, due to the implementation of efficient accumulator batteries (a similar phenomenon is observed for electric vehicles). Trolleybuses equipped with accumulator batteries are an interesting development, allowing the advantages of both the electric bus and the trolleybus to be used, with an increased range compared to the first one. The advantage of the electric bus/trolleybus compared with the tram is greater adhesion to the ground, which favours the construction of trolleybus lines in the towns located in mountainous or hilly areas (e.g. Gdynia), the disadvantage is lower transport capacity. This factor results in trams operating in medium to large sized towns, trolleybuses in medium sized towns and electric buses in small or medium sized towns, which also avoids the cost of hanging the overhead contact lines.

Fig. 2. The Solaris Trollino 12T 1st generation trolleybus, pl. Konstytucji, Gdynia (13/11/2010) [photo M. Graff]

Fig. 3 The Solaris Urbino 12 electric bus, Pawia Street, Cracow (29/10/2016) [photo M. Graff]

The construction of the metro is carried out when the population of a city or agglomeration exceeds 1 million inhabitants, because only then is a high transport capacity a prerequisite for the effectiveness of the metro, despite the high costs of building the infrastructure (tunneling). The metro is also independent of urban or railway infrastructure, as it uses its own (with a few exceptions, such as selected sections of the London Underground). In cities with several million inhabitants (London, Paris, Seoul, Tokyo, etc.), the metro is the primary mean of transport, and the shutdown of even 2–3 lines sometimes causes the city paralysis. One way to reduce the cost of constructing the metro network is to build overground sections, which is widely practiced in London, for example, because of the development of the suburbs (in other cities, overground sections are rather the exception).

Monorail, including suspension or magnetic levitation, is used in the cities where high land prices or a lack of space does not allow the construction of another mean of transport (Fig. 4 and 5). For this reason, monorail is popular in Japan, while in Europe it is more of an exception (e.g. Wuppertal in Germany). The low prevalence causes individual manufacturers to use their own technical solutions, which also results in a high incompatibility of systems.

Urban rail enables trains to run on the existing railway infrastructure and transport people from the suburbs or satellite towns to the centre (Fig. 6). However, the considerable distance between stops (> 2–3 km) makes it a complement but not a substitute for public transport. The public transport of Berlin is an interesting example – the metro (U-Bahn) is used for medium-distance travel within the city, the urban rail (S-Bahn) for medium or long distances, possibly within the agglomeration. Furthermore, the Berlin S-Bahn uses its own infrastructure and is therefore independent of the railway infrastructure. As both systems are extensive (most districts have access to at least one of the systems), getting around the German capital is not an issue.

Fig. 4. The suspension railway in the vicinity of Uferstraße, Wuppertal, (8/05/2010) [photo Mbdortmund / Wikimedia Commons]

Fig. 5. The magnetic levitation railway constructed using Siemens technology, Moscow (18/06/2007) [photo P. Czech]

Fig. 6. The Impuls 31WEb-005 / 605 set of the FUR Warsaw at Warsaw Zachodnia station (20/04/2022) [photo M. Graff]

Urban railway systems of Warsaw or Cracow make use of the existing railway network and ensure communication of satellite towns or suburbs with the city centre and supplement the existing transport offer provided by the local self-government carriers (Mazovian Railways / Lesser Poland Railways) or national operator (POLREGIO). In Warsaw, the putting into service of individual Fast Urban Railway (FUR) lines

has also been an impetus for the revitalization of existing railway lines or the reconstruction of the existing track layout, which has been found to be inefficient, or the construction of short sections of new lines (e.g. to the civil Warsaw Chopin Airport, LK 440; the planned line to the civil airport in Modlin[2]). Urban rail, due to its high transport capacity, can also be used to transport people from office districts or satellite towns. A systemic limitation of the FUR in Warsaw and Cracow is the dependence on the railway infrastructure, which also limits the capacity of the systems. In Cracow, the expansion of the FUR involved, inter alia, the rebuilding of 5 km of track on the busiest section of Kraków Gł. – Kraków Płaszów (LK 91), from a 2-track to a 4-track section (which significantly increased capacity, also by separating suburban and long-distance traffic), with the section on an earth embankment, constructed in the mid-19th century, being replaced by a section on an overpass. For the purpose of increasing the efficiency of the Cracow agglomeration railway, new stops are being added in the vicinity of commercial facilities or housing estates, and a connection to the Balice civil airport has been provided (the existing line has been modernised)[3].

In Warsaw, the construction of the metro has been promoted for the last 10–15 years as the most efficient transport system – tram and bus transport, although well developed, has become too time-consuming (travelling from one end of the city to the other already takes about one hour). Although the new tram lines (to Wilanów, via the West Station) or the aforementioned FUR are under construction, the authorities of Warsaw have recognised the metro as the primary mean of transport. The EU aid funds are being used extensively.

This article presents the extension of the 2nd line of the Warsaw Metro, running in the east-west direction (Fig. 7). As of March 2015, when the central section of the 2nd line was opened, the number of passengers on the 2nd line was low due to its considerable

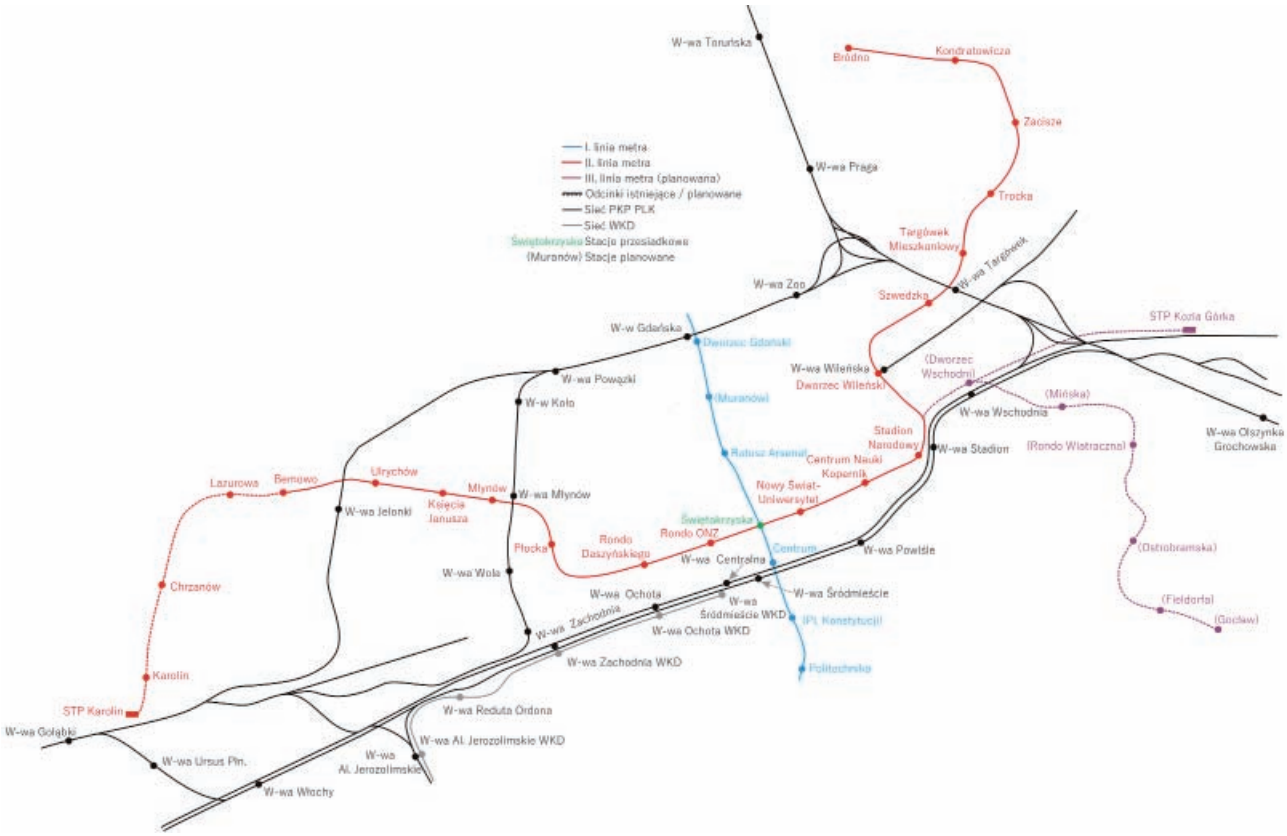

Fig. 7. The scheme of the 2nd line of the metro in Warsaw [own elaboration]

[2] It is a former military airport, used between 1940 and 2000, has been operating as a civilian airport since 2010 and has been performing (albeit intermittently) regular flight operations since 2012.

[3] The authorities of Cracow would like to incorporate into the urban railway system also services on the ring line (LK 95) running close to the former T. Sendzimir Steel Plant; however, the line – constructed for freight transport, runs at a considerable distance from residential areas, which does not guarantee an acceptable level of transport volume.

distance from the housing estates. It was only the commissioning of the sections running through the districts such as Wola and Bródno, which are the bedroom areas of Warsaw, that resulted in a significant increase in the number of passengers. The modern Varsovia trains, similar to the Inspiro trains provided by Siemens and used by the Warsaw metro, have been purchased from Škoda to service the line. Along with the acceptance of the next Varsovia trains, the non-modern 81-series rolling stock of the eastern production, for which a purchaser has been found – the Kyiv Metro – will be decommissioned. The final stage of the extension of the 2nd line will be the section in the south-western part, which also includes the construction of the Karolin technical and holding station (STP Karolin), a repair and maintenance facility for the 2nd line and will significantly relieve the Kabaty technical and holding station (STP Kabaty), where all metro trains are currently stationed and serviced. The most meaningful difference between the construction of the 1st and 2nd metro lines are not only the method of construction (1st line has been constructed from the south to the north, 2nd line – first the central section, then branches in both directions), but also the technology used respectively manual excavation / with TBM, for the 1st / 2nd line with a capacity of 3 / 20–30 m per day [1]. The construction of the 2nd line is co-financed by the EU aid funds [2, 3, 4].

2. Eastern section of the 2nd line

The first stage of the implementation of the eastern – northern section of the 2nd metro line in Warsaw, is located in two districts (Praga Północ and Targówek) in the eastern-northern part of Warsaw. In mid-September 2019, the north-eastern section, of the 2nd metro line in Warsaw, 3.2 km long, with 3 stations, was commissioned: Szwedzka, Targówek Mieszkaniowy and Trocka, so at the time the second metro line was 9.7 km long and had 10 stations (Fig. 8). The construction funds of approximately 1.07 billion PLN came 75% from the EU co-financing. The new stations were built: Szwedzka / C16 – the area of Szwedzka Street and Strzelecka Street, Targówek Mieszkaniowy / C17 – the area of Pratulińska Street and Ossowskiego Street, and the last station Trocka / C18 – at the intersection of Pratulińska Street and Trocka Street. Behind the C17 station, a turnout chamber has been created and behind the C18 station, there are the side tracks. The station décor is simplistic, even stark, with white, black, and grey colours used. Rounded panels with the addition of perforated metal have been used for finishing the walls and ceilings of the stations, light granite has been used for the floors and the columns are made of architectural concrete. Dark grey architectural concrete panels have been used for the entresol walls. The difference in the arrangement of the individual stations is the patterns of the concrete panels and, in addition, clinker brick has been used at the C16 station. The contractor was Astaldi, which signed the construction contract with the city authorities in mid-March 2016. Work began just one month after the contract was signed, with tunneling starting in May 2017 from the launch shaft at the C18 station. Two tunnel boring machines (TBMs), which had previously been used to excavate the central section of the second metro line, were used. Completing the tunneling in January 2018, a total of 2.2 km of tunnels (not including the station sections) were excavated. The first test train entered the new section of the second line in January 2019. Although Astaldi has had problems with contracts in Poland (e.g. with the modernisation of the LK 7), this does not apply to the extension of the Warsaw metro. A use permit to use all facilities of the north-east section up to the C18 station was issued by the Provincial Construction Inspector in early September 2019. Traction service on the second metro line required 3 more trains than before the handover of the new section (15 instead of 12).

Fig. 8. The Trocka station (15/09/2019) [photo M. Graff]

Tunneling on the north-eastern section of the 2nd line of the metro started in May 2020 at the C21 Bródno station to the side tracks of the C18 Trocka station [5]. The construction cost of the section was PLN 1.398 billion and a consortium of Gülermak and Astaldi companies were selected as the contractors. Within the C21 Bródno station, the construction of a chamber with 11 side and turning tracks was anticipated. Three years were scheduled for the work, with a completion date of September 2021, but due to the coronavirus pandemic, the contractor, Gülermak, requested a postponement of nine months. So the TBM Anna and Maria were transported to the construction of the north-eastern section, where TBM Anna started work at the station

(C21 Bródno → C18 Trocka) with an impressive capacity of 30 m per day [6].

Test runs of the trains began in early August 2022, with finishing and acceptance work being carried out at the stations [7]. The section to the Bródno station opened at the end of September 2022 [8]. The station design has been carried out by ILF, as has the previous eastern section of the 2nd line. The stations have a modest, even stark appearance maintained in white and grey colours similar to the colours of the previous section, although different solutions and materials have been used. Thus, white terrazzo tiles have been used to line the side walls, granite for the floors, and a form of the grate of grids in the antresole for the ceilings. The ceilings on the platforms are razor-shaped. Architectural concrete has been used to finish the columns. The side walls of the stations feature panels with colourful graphics by P. Młodożeniec. The arrangement of each station is made with different motifs of spots, composed of squares, dots and lines, with different colours used at each station (Fig. 9–13):

- Bródno – violet and navy blue,
- Kondratowicza – tiger stripes with warm patterns – yellow, orange, and, red,
- Zacisze – green.

Fig. 9. The entrance to the Bródno station (18/03/2023) [photo M. Graff]

Fig. 10. The Bródno station (18/03/2023) [photo M. Graff]

Fig. 11. The Zacisze station (01/10/2022) [photo A. Grycuk / Wikimedia Commons]

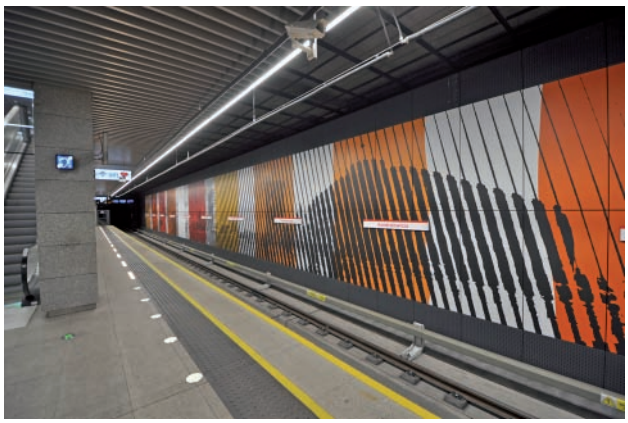

Fig. 12. The Kondratowicza station (18/03/2023) [photo M. Graff]

Fig. 13. The Bródno station (01/10/2023) [photo A. Grycuk / Wikimedia Commons]

At the Bródno station, the previously mentioned track layout is very extensive, and the branch tracks begin even before trains reach the platforms (from the Kondratowicza station side). The station covers as much as 3 hectares and approximately 250 rooms. For the first time in the metro there are 2 moving

walkways, 50 and 36 m long and 1 m wide, in the tunnel leading in the pedestrian section towards św. Wincentego Street towards the future tramway line to Zielona Białołęka.

3. Western section of the 2nd line

The western section of the 2nd metro line in Warsaw constituting the 2nd stage of its implementation in this area of the city is located in the Wola and Bemowo districts. In the majority of the section, the metro route runs under Górczewska Street, in the eastern part of the section under the northern roadway, then under the southern roadway with a slight deviation to the south at the intersection of the street with the railway line.

The gross capital expenditure for the construction of the aforementioned section is PLN 1.148 billion. Work began at the end of November 2016, and tunnelling was carried out from February to September 2018 from the starting chamber at the Księcia Janusza station in the eastern direction (Maria TBM), at an average speed of 18 m per day (southern tunnel). In the opposite direction, the Krystyna TBM worked at a speed of 22 m per day (north tunnel), with a record speed of 36.5 m per day. Track laying and installation of equipment in the tunnels was carried out between January and November 2019. The length of the railway platforms is 120 m and the longest station is the Księcia Janusza station – 606.1 m due to the presence of a side track chamber for up to 8 trains (Płocka and Młynów stations - 163.6 m and 168.2 m, respectively). In March 2020, the acceptance of 3 new stations on the western section of the 2nd metro line – the C8 Płocka, C7 Młynów and C6 Księcia Janusza where carried out, with a planned commissioning date of early April 2020 [9–11]. Prior to this, the Rondo Daszyńskiego station had to be closed for 7 days to connect the power and control systems of the new section with the existing metro network. The stations were arranged as follows (authorship – Biuro Projektowe Kazimierski i Ryba (Kazimierski and Ryba Design Office):

- C8 Płocka – the copper panels in a uniform colour (on the entresol) or alternatively in the shades (on the platform) were used, which is a reference to the industrial history of Wola and the characteristic geometry of integrated circuits (former consumer electronics factories)[4]; the stairs to the railway platform were covered with milky panels, Corian benches and the platform floor was covered with bright terrazzo;
- C7 Młynów – the decoration of the station, with its specific ponds, is a reference to the pools and ponds located in the nearby Moczydło Park;
- C6 Księcia Janusza – the reference to the Ulrich Gardens, where the former buildings and some specific plant species have been preserved.

The new section runs from the track behind the C9 Rondo Daszyńskiego station to the side tracks behind the C6 Księcia Janusza station. The western section of the 2nd metro line in Warsaw, which is the first stage of its completion in this area of the city, is located entirely within the Wola district. (Fig. 14–17). From the track behind the side tracks of the C9 Rondo Daszyńskiego station, the metro route initially runs under Kasprzaka Street and then, passing under the built-up area turns north into Płocka Street. To the north of Wolska Street, the line turns west, passing under the existing residential development and runs under ul. Górczewska. The metro line passes under the existing PKP overpass and under the overpass of Prymasa Tysiąclecia Avenue. Continuing westwards under Górczewska Street, the line passes through the green areas (Park named after E. Szymański, Moczydło Park), and then after the intersection with ul. Deotymy through the areas with nearby residential and commercial development. The then end of the line, together with the side tracks, was located in the area of the eastern entrance to the 'Wola Park' shopping centre at the level of Krępowieckiego Street.

Fig. 14. The ticket gates at the Księcia Janusza station (04/04/2020) [photo M. Graff]

[4] In the Wola district there was, inter alia, Warszawska Spółka Akcyjna Budowy Parowozów (Warsaw Steam Locomotives Construction Company).

Fig. 15. The entrance to the Księcia Janusza station (04/04/2020) [photo M. Graff]

Fig. 16. The Księcia Janusza station (04/04/2020) [photo M. Graff]

Fig. 17. The Płocka station (04/04/2020) [photo M. Graff]

As the section to the Księcia Janusza station has been opened, work has commenced on the next western section of Line II [12, 13]. In mid-May 2020, the transport of the Krystyna and Elisabetta TBMs, weighing 650 t, 100 m long, and 6 m in diameter (Metro has ordered 4 similar TBMs), began and they were dismantled for the transport. It takes about 1 month to assemble the disc cutter and prepare it for operation. The TBM is operated by 12 people in 4 shifts, with the operation of the machine being fully automated. The drive of the TBM is provided by 16 pairs of hydraulic cylinders. The TBM operates continuously and the operation of the disc cutter is interrupted when, for example, cutting blades need to be replaced, or when there are problems with the ground. The starting shaft has been selected at the site of the side tracks at the future C4 Powstańców Śląskich station after the construction of about 150 m of foundation slab. In the excavated tunnels, some 1,370 m long, 1,824 tubings (tunnel structural elements) of 1.5 m in length each have been laid. The cost of building the tunnels and 2 stations: the C5 Ulrychów and C4 Powstańców Śląskich is PLN 959 million, using EU aid funds. Construction of the section should have been completed in November 2021, but there has been a delay due to the pandemic (the contractor has requested an 8-month postponement of the time limit).

The section from the Księcia Janusza station to the Bemowo station was opened at the end of June 2022 [14–16]. According to the Warsaw authorities, the EU has provided financial support for the 2nd metro line for PLN 7 billion, and it is now problematic to obtain further funds due to the funds blocked from the National Reconstruction Plan (Krajowy Plan Odbudowy). The decoration of both stations – Ulrychów and Bemowo have been designed by the architect A. Chołdzyński with the Metroprojekt company (Fig. 18–21). The wave-shaped elements, corten, acoustic plaster with a lamb structure, and stone and coloured mosaics next to the stairs have been used to arrange the stations. To cover the floors, the side walls of the platforms granite (panels made of perforated sheet metal arranged in the form of sharp-ended waves) have been used, with copper metal sheet of a greenish shade used at the C5 Ulrychów station and COR-TEN® steel at the C4 Bemowo station (the aforementioned material will, over time, have a characteristic rust colour). The ceilings at both stations have been arranged with square coffers of a chocolate shade, with the coffers at the Bemowo station being arranged diagonally and at the Ulrychów station parallel to the track. The clinker wall panels have been installed on the entresols. The extension of the 2nd metro line will increase the number of trains needed to serve the line from 18 to 21 with an unchanged frequency of 2 min 50 s. (There are 36 trains on the 1st metro line). After the latest extension, the 2nd line is 18.9 km long and features 18 stations, spaced on average every 1.0 km. For comparison, the corresponding ratios for the 1st line is 22.7 km and 21 stations, with station spacing averaging every 1.1 km. The characteristics of the new sections and stations on the 2nd line of the metro are given in Tables 2–5 (eastern section) and the Tables 6–9 (western section).

Fig. 18. The Elisabetta TBM in the area of the future Bemowo station (13/06/2020) [photo M. Graff]

Fig. 20. The Bemowo station (11/03/2023) [photo M. Graff]

Fig. 19. The entrance to the Bemowo station (11/03/2023) [photo M. Graff]

Fig. 21. The Bemowo station (21/06/2022) [photoA. Grycuk / Wikimedia Commons]

Table 2

Eastern section [17, 18]

Facility or process	1st stage	2nd stage
Extension of the 2nd metro line includes	construction of the east-north section from the track behind the C15 Dworzec Wileński station to the side tracks behind the C18 Trocka station	construction of the east-north section from the track behind the C18 Trocka station to the side tracks behind the C21 station
Number of stations	3	3
Stations	C16 – Szwedzka, C17 – Targówek, C18 – Trocka along with route tunnels	C19 – Zacisze, C20 – Kondratowicza, C21 – Bródno along with route tunnels
Number of route ventilation shafts	3	3
Route ventilation shafts	V16, V17, V18	V19, V20, V21
Number of route tunnels	3	3
Route tunnels	D16, D17, D18	D19, D20, D21
Dismantling chamber	(name missing)	C18 (KD C18)
Section length [km]	3.2	3.9
Total length of tunnels [m]	6290.7	5785
Total cubic area of facilities (stations and route ventilation shafts) [m^3]	422 800	672 179
Commissioning	September 2019	September 2022

Table 3

Location of stations in the eastern section [17, 18]

Station	Location
C16 Szwedzka	under Strzelecka Street near the intersection with Szwedzka Street, in the area between the Strzelecka 46 building and the area of the Stalowa Bus Depot of the Municipal Transport Company (MZA).
C17 Targówek	under the intersection of Pratulińska and Ossowskiego streets in the Targówek district. On the northern side of Ossowskiego Street, a one-storey underground structure of a turnout chamber connecting to the station has been located under the green area.
C18 Trocka	along Pratulińska Street, under the intersection of Pratulińska and Trocka Streets, as well as along the newly designed street on the extension of Pratulińska Street.
C19 Zacisze	along Figaro Street at the intersection with Codzienna, Rolanda, and Spójnia Streets.
C20 Kondratowicza	along Kondratowicza Street between the intersections with Malborska and 20. Dywizji Piechoty WP streets and the intersection of Św. Wincentego Street with Kondratowicza Street. Planned link from the metro station to the planned tram stops on Św. Wincentego Street.
C21 Bródno	located along Kondratowicza Street between the intersections of Bazyliańska/Rembielińska and Łabiszyńska Streets. A station with two turnout chambers and side tracks.

Table 4

Technical data of the tunnels – the eastern section [17, 18]

Facility length [m]	1st stage	2nd stage
Length of right track tunnel	4020.6	3135.4
Length of left track tunnel	3993.2	3155.3
Station length	176.0 – C19 314.0 – C20 697.5* – C21	135.3 – C16 299.0 – C17 KR 450.0 – C18 TO
Length of dismantling chamber station	31.0 (at the C18)	~ 20.0 (at the C15)
Total length of tunnels	5785.0	6290.7
Top of rail level (TRL) under ground level	9.0 – 13.9	11.9 – 16. 2
Average top of rail level (TRL) under ground level	11.5	14.0

* Of the station and side tracks.

Table 5

Technical data of cubature objects – the eastern section [17, 18]

Facility [m^3]	1st stage	2nd stage
Stations	62 674.0 – C16 105 553.0 – C17 227 372.0 – C18	74 199.0 – C19 93 420.0 – C20 469 891.0 – C21
Route ventilation shafts	6455.0 – V16 7761.0 – V17 5267.0 – V18	9158.0 – V19 8817.0 – V20 8875.0 – V21
Dismantling chamber	7718.0 (C15)	7819.0 (C18)
Total cubic area of facilities	422 800.0	672 179.0

* Of the station and side tracks.

Table 6

Technical data of cubature objects – the western section [17, 18]

Facility or process	1st stage	2nd stage
Extension of the 2nd metro line includes	construction of the western section from the track behind the C9 Rondo Daszyńskiego station to the side tracks behind the C6 Księcia Janusza station	construction of the western section from the track behind the C6 Księcia Janusza station to the side tracks behind the C4 Bemowo station
Number of stations	3	2
Stations	C6 – Księcia Janusza, C7 – Młynów, C8 – Płocka along with route tunnels	C4 – Bemowo, C5 – Ulrychów along with route tunnels
Number of route ventilation shafts	3	1
Route ventilation shafts	V9, V8, V7	V5
Number of route tunnels	3	2
Route tunnels	D9, D8, D7	D5, D6
Dismantling chamber	V9A	S6
Section length [km]	3.4	2
Total length of tunnels [m]	5047	2 664
Total cubic area of facilities (stations and route ventilation shafts) [m³]	341 330	295 602
Commissioning	04/2020	06/2022

Table 7

Location of stations in the western section [17, 18]

Station	Location
C8 Płocka	under Płocka street, in the area of the intersection with Wolska street.
C7 Młynów	under Górczewska Street, located between the railway line bridge (LK 20) and Syreny Street.
C6 Księcia Janusza	under ul. Górczewska, in the area of the intersection with ul. Ksiecia Janusza, on the eastern side of the intersection.
C4 Ulrychów	along Górczewska Street under its southern roadway.
C5 Bemowo	along Górczewska Street under its southern roadway, in the area of the intersection with Powstańców Śląskich Street.

Table 8

Technical data of the tunnels – the eastern section [17, 18]

Facility length [m]	1st stage	2nd stage
Length of right track tunnel	3481.6	1986
Length of left track tunnel	3477.7	1988
Station length	606.1 – C6* 168.2 – C7 163.6 – C8	459** – C4 160 – C5
Length of dismantling chamber station	18.3	18
Total length of tunnels	5047.0	2664
Top of rail level (TRL) under ground level	12.3 – 18. 2	13.7 – 14.7
Average top of rail level (TRL) under ground level	15.2	14.2

* Of stations and side tracks.

** Of turnout chamber and side tracks.

Table 9

Technical data of cubature facilities – the western section [17, 18]

Facility [m³]	1st stage	2nd stage
Stations	188 480.9 – C6 56 636.6 – C7 59 198.0 – C8	224 586 – C4 60 272 – C5
Route ventilation shafts	11 228.4 – V7* 6 459.2 – V8 9 674.5 – V9	4 302 – V5
Dismantling chamber	9 652.4 – V9a	6442 – S6
Total cubic area of facilities	341 330.0	295 602

4. Last section of 2nd metro line (under construction)

In May 2020, the Masovian Voivodship issued the first location decisions for the last section of the 2nd metro line (C4 Powstańców Śląskich – C1 Karolin together with the Karolin technical and holding station (STP) [19]. As of November 2017, the tenders of the two participating entities were higher by PLN 0.4 billion than the originally allocated funds (PLN 1.2 billion), the city authorities decided to increase the budget. The value of the contract is PLN 1.623 billion gross. The contract for the construction of the section was signed in November 2018 with a consortium of Gülermak and Astaldi, with a completion time of four years [20]. The design of the section is being carried out by ILF Consulting Engineers. Numerous obstacles have been encountered in obtaining:

- a new environmental impact decision,
- a location decision (so-called DLRL – the decision on the location of the railway line),
- as well as the need to resolve problems due to protests by landowners.

Six location decisions are required (3 stations, 2 ventilation shafts and 1 technical and holding station (STP). The new section will include 3 stations: C3 Lazurowa, C2 Chrzanów and C1 Połczyńska, in the vicinity of which the Karolin STP will also be located, delimited by railway tracks in an area of 26 ha. Within the new technical and holding station (STP), the following will be constructed:

- administration building,
- train turnaround loop,
- test track,
- electric locomotive shed,
- rolling stock repair hall,
- washing plant,
- signal box,
- traction substation,
- special rolling stock depot,
- fire station building,
- a warehouse for flammable materials and technical gases,
- sewage treatment plant,
- infrastructure service workshops,
- sub-track lathe and paint shop,
- diesel locomotive depot,
- petrol station.

In mid-July 2022, the Masovian Voivodship issued a construction permit for 2 of the 3 stations [21, 22]. In total, 9 permits must be issued, separately for each of the stations, the route ventilation shafts, the technical and holding station (STP), the launch shaft for the TBM and the dispatching facility of the Metropolitan Transport Authority (ZTM) at the Górczewska housing estate loop. It is estimated that the width of these stations is > 10 m, which will be arranged as follow:

- side walls – coloured architectural concrete,
- floorings – marble, artificial stone with terrazzo texture,
- ceiling – suspended, made of perforated sheet metal (30%), with a grid structure and light grey colour scheme,
- side walls of the platform – made of panels, made similar to the ceilings,
- lighting – LED,
- connection of the entresols to the platforms – stairs (moving staircases and regular stairs) and lifts.

A significant concern is a change in market conditions – an increase in material prices (e.g. steel by 73%, copper by 37%), higher inflation (3.5% in January 2021), average remuneration (from PLN 2,100 to PLN 3,010), etc., as well as the need to change the design documentation and environmental impact assessment. Thus, the existing 2018 contract worth PLN 1.6 billion signed under the 'Design and Build' formula needs to be modified, i.e. valorised. In 2019, the difference was already several hundred million PLN, and the pause in construction and the passing of time increases this amount, not decreases it. Initially, it was assumed that the construction would be carried out in four years and completed in November 2022 [23]. Although an amending annex was signed in 2020 (the city authorities and the contractor) providing for an extension of the works by 18 months, i.e. until May 2024, this time limit also does not appear to be feasible. In total, the bank guarantees (PLN 75 million) have become lower than the aggregate increase in the price of materials and workmanship. As both the city authorities and the contractor are interested in further cooperation, litigation is unlikely. Ultimately, the objective of the Warsaw authorities are to complete the construction of the 2nd underground line, including the Karolin STP, so it will be necessary to raise additional funds despite tough negotiations announced by the president of the Turkish company Gülermak, which is also executing other construction contracts in Warsaw. The characteristics of the stations on the last section of the 2nd metro line are presented in Table 10.

5. Technologies used during the expansion of the 2nd metro line

Most of the same technologies have been applied during the extension of the 2nd metro line as in the construction of the central section of the 2nd line [2].

Table 10

Station characteristics of the final section of the 2nd metro line [24]

Station	Location	Comments
C3 Lazurowa	in the area of the intersection of Lazurowa and Górczewska streets and the bus terminal	will be an element of a transport interchange, comprising a bus terminal, a tram terminal and a P&R car park. The location of the junction will make it possible to transfer traffic to Warsaw from the western direction.
C2 Chrzanów	under Rayskiego Street in the area of the intersection of Rayskiego and Szeligowska Streets	planned parking for bicycles
C1 Karolin	under Sochaczewska Street in the area of the intersection of Sochaczewska and Połczyńska Streets	will be an element of the traffic interchange with a P&R car park and will enable traffic to be transferred to Warsaw from the western direction
STP Karolin	the area of the Karolin technical and parking station is bordered by the PKP railway infrastructure to the south, the Power Engineering Institute to the north, 4 Czerwca 1989 Avenue (Nowolazurowa Street) to the east, Gierdziejewskiego Street to the west (Ożarów Mazowiecki municipality)	–

Construction of the stations

The stations have been constructed using the so-called floor method. In the first stage, vertical slurry walls have been erected, consequently forming the target floor (by horizontal overlapping between the walls), from under which the soil has been excavated [25]. The aforementioned walls acted as shoring for deep excavations and the foundation of buildings. Their purpose has been to carry loads caused, for example, by lateral soil pressure, hydrostatic pressure, or vehicle traffic on the ground surface. Slurry walls are built in stages of several metres in length, with pipe-shaped or flat distribution elements with additional seals used in between. The depth of the wall is usually < 0.3 m. The construction of the walls is carried out in several stages:

- removal of obstacles (e.g. utility connection),
- assembly of guiding walls, e.g. in reinforced concrete,
- during excavation, the slot is filled with a betonite suspension, which ensures the stability of the vertical surfaces of the hole,
- cleaning the suspension after reaching the desired depth,
- assembly of reinforcement on the guiding walls,
- concreting the walls with the use of contractors and pouring pipes.

The concrete mix, due to its higher density (specific gravity), displaces dirt and suspension upwards from the slot. The main advantages of slurry walls are as follows:

- tightness of support;
- high vertical load-bearing capacity;
- significant bending stiffness;
- its role as temporary support of the excavation and, in parallel, of the target structure;
- absence of vibration during construction;
- relatively high simplicity of overcoming ground obstacles;
- possibility of constructing the wall to great depths.

Tunneling with TBM

The TBM have been fitted with watertight covers, located on the cutting head and at the rear. The disc cutter is isolated from the influence of ground pressure and groundwater. On the other hand, the excavated material collected in the chamber creates pressure on the side of the disc cutter that balances the pressure of the ground and groundwater. From there, the excavated material is transported by means of a screw conveyor to conveyor belts and removed from the tunnel. Once a sufficient distance has been excavated, the excavating disc and the screw conveyor stop, and the tunnel ring laying module (tubing) is activated. Each prefabricated piece is laid so that it fits tightly against the previous ring and the elements of the new ring. The gap formed between the outer wall of the tunnel and the ground is filled with mortar, injected using high-pressure nozzles.

Jet-grouting, i.e. stream injection, is a method of soil reinforcement and stabilisation. A cement suspension is injected under high pressure, so a cylinder-shaped column is formed within the soil to reinforce the soil – both at the injection site and in the vicinity of the work carried out.

6. Metro rolling stock – the Varsovia trains

The contract for the delivery of metro trains for the Warsaw metro railway was signed with Škoda in January 2020 for 37 single-space 6-carriage metro trains, with an option for the delivery of a further eight units.

The value of the contract is PLN 1.308 billion net. Due to the outbreak of the Covid-19 pandemic in March 2020, the delivery dates or dates of authorisations to operate were eventually changed [26]. The first Varsovia train was delivered to the customer in April 2022. Test runs on the metro network were carried out at night. Following their completion, the results of the technical and operational tests and an application to obtain a type approval certificate and a decision approving the maintenance system documentation (MSD) in mid-August 2022 were sent to the Office of Rail Transport (UTK) [27, 28]. At the end of September, the UTK issued an authorisation to operate the type of vehicle for a limited period of time, which allowed operational tests to be carried out. In October 2022, representatives of the Warsaw metro informed that Škoda had received a set of documents from UTK (among other things, the DSU needed to be detailed), which enabled the Varsovia trains to start operating with passengers. In November 2022, the Warsaw metro authorities reported that three Varsovia trains were in service [29]. The new trains were not spared from 'childhood diseases', with the most common reasons for running off the line being failures of the TFT panels, intercom operation, securing the second cab, and possibly ramp failures. A separate problem was that only 1/5-1/6 of the metro drivers employed were qualified to drive the new trains. In January 2023, 7 Varsovia trains were in operation and another was delivered to Warsaw Okęcie station, from where it was transported to the Kabaty technical and holding station (STP) [30]. In addition to this, the metro authorities signed a contract with the manufacturer to exercise an option for a further 8 trains – the authorities decided that a final decision was to be made by the end of March 2023. Škoda, however, accepted the argumentation that, at that time, the new rolling stock had only been in operation for 2.5 months, so the necessary additional time was negotiated, for learning the specifics of the operation of the Varsovia trains and gathering passenger feedback.

7. Technical description of the Varsovia trains

The train bodies are made of aluminum alloy, except for the driver's cabs, which are made of laminate elements [31] (Fig. 22–25). The bogies are connected to the body by a bogie pivot fixed to the body and fixed and pivotable buffers fixed to both the pivot and the bogie frame. The guidance of the wheelsets is columnar. The suspension is of two stages:

- the 1st stage of suspension consists of metal-rubber springs, 4 elements in total per wheelset, vertical dampers of the 1st stage of damping (2 dampers per wheel set),
- the 2nd stage of suspension – air springs, 2 elements in total per bogie, plus 2nd stage vertical dampers (2 at each bogie) and transverse dampers (1 per bogie).

Fig. 22. The control panel on the Varsovia train [photo: Škoda]

Fig. 23. The passenger section of the Varsovia train [photo: Škoda]

Fig. 24. The Varsovia train on the premises of the manufacturer [photo: Škoda]

Fig. 25. The Varsovia train on the premises of the manufacturer [photo: Škoda]

In each drive carriage, a traction container containing 2 traction converters made using the IGBT technology is installed under the body frame. Each traction converter supplies 2 motors per bogie (parallel connection). The auxiliary converters are installed under the carriage frame in both rolling carriages. In addition to the on board 110 V DC power supply, they also provide a 400 V 3~ power supply, whereby vehicle operation is possible with one operational converter. Under the body frame of the rolling carriages are, mounted accumulator battery boxes. In total, there are 2 Ni-Cd accumulator battery banks with fibrous electrodes in the train. The primary brake is an electrodynamic regenerative brake and braking resistors allow electrodynamic braking in the event that energy cannot be returned to the overhead contact line. The secondary brake is an electro-pneumatic brake and a spring-loaded parking brake. One brake disc is installed on each wheel set (driving and rolling). Operation in multiple traction is possible, but not implemented. Due to the length of the platforms being 120 m, the use of multiple traction on the Warsaw metro is not possible. Due to the length of the platforms of 120 m, the use of multiple traction on the Warsaw metro is not possible. The on-board train control system is based on the Škoda Hypex platform and is integrated with the on-board equipment of the SOP-3 system used by the Warsaw metro. Currently, on the 2nd line of the Warsaw metro, the driver is responsible for starting the vehicle (moving off the station platform) and closing the doors. The remaining operations on the 2nd line (starting, maintaining speed, braking, including target braking on the platform and opening the doors) are performed automatically, without the driver's involvement. The SOP-3 system used on the 2nd line of the Warsaw metro enables fully autonomous driving but is unable to react to unpredictable situations (e.g. a person on the tracks). Therefore, in order to enable fully autonomous driving, it would be necessary to install glass walls with doors on the platforms, which would only open upon arrival and open the doors on the vehicle. Apart from the technical adaptation, the legislation would also have to be adapted. The service cycle of the metro trains is not known (this information is not disclosed by the Contracting Authority). The arrangement of the passenger section is similar to that of the Inspiro analogue one – the trains are passable and passenger seats are placed along the side walls. The interior colour scheme is also similar – white panels lining the side walls and ceiling, red seats, and yellow handrails. Detailed technical data for Varsovia trains is provided in Table 11.

Table 11

Technical data of the Varsovia trains [31]

Manufacturer	Škoda Transportation a.s.
Trade name	Varsovia
Type	59WE
Number of trains ordered	37+8
Years of production	2021–
Start of operation	2022
Making up of train	St–S–D–D–S–St
Axle configuration	2·(Bo'Bo') + 2·(2'2') + 2·(Bo'Bo')
Body	aluminium
Power supply	750 V DC
Maximum continuous power of traction motors [kW]	2400
Overall length [mm]	119 010
Length of end/centre coaches [mm]	20 305 / 19 600
Coach base [mm]	12 600
Bogie base [mm]	2100
Maximum width [mm]	2710
Height [mm]	3665
Height of floor top of rail level [mm]	1140
Diameter of new/worn wheels [mm]	850 / 770
Maximum traction force [kN]	432
Maximum acceleration/deceleration [m/s²]	1.2 / 1.3
Resistance of boxes to compression [kN]	800
Maximum axle load [kN]	125
Maximum inclination [‰]	45
Minimum radius of horizontal curve [m]	70
Maximum speed [km/h]	90
Weight of train without passengers [t]	160.4
Weight of train with passengers (seated + 7 people/m²) [t]	265.4
Seating capacity	230
Standing capacity (7 people/m²)	1270

8. Further fate of series 81 in the Warsaw metro

The Warsaw metro has been preparing for the end of operation of the 81 series for several years due to the need for significant maintenance and repair expenditures, which contrasts with the new generation rolling stock, equipped with a commutator and maintenance-free three-phase (DC vs. AC 3~) motors, respectively[5]. Illustratively, the 81 series undergoes the P1 maintenance every day, the Metropolis every 2 weeks and the Inspiro every 2 months [32]. In May 2021, for the last 81-series trains manufactured, 28 carriages (8 front carriages of series 81-572.2 and 20 intermediate carriages of series 81-573.1 and 81-573.2) have been tendered for the P5 repairs, which include [33]:

- repair and replacement of windows
- painting of the body,
- removal of corrosion centres,
- reconditioning of the driver's control panels,
- replacement of floor covering and plywood,
- painting of under-seat covers,
- repair of flaps in the floor,
- replacement of skirting boards, door rollers, door buses and worn handrails.

Furthermore, an inspection of member welds, geometry measurements and leakage tests are required. The selection criterion is:

- price (60%),
- extension of the warranty period (24%),
- shortening the repair time for each individual 6- or 4-carriage batch of carriages (16%).

The last 81-series carriages for the P5 repairs will be dispatched in 2023, with 4–6 carriages taking a maximum of 60 days to repair (Fig. 26). The tender was awarded at the end of June 2021 and the order went to the Rail Rolling Stock Repair Workshops (ZNTK) Mińsk Mazowiecki (owned by Pesa since 2008), with it being the only tenderer. The value of the order was set at PLN 7,742 million gross, which is lower than the budget that the metro authorites had prepared (PLN 9,694 million gross) [34].

At the same time, the delivery of the new Varsovia metro trains will make it possible to withdraw the oldest rolling stock, i.e. the 81 series eastern production carriages, which the Kyiv metro authorities are interested in acquiring. On this matter, the International Association of Polish Entrepreneurs in Ukraine, which brings together, inter alia, the Polish entities operating in the rail sector in Ukraine, and 2 representatives of two Ukrainian entities visited the Warsaw metro authorities, where the feasibility of adapting rolling stock from Warsaw for the Kyiv metro was discussed [35]. Although the 81-series metro carriages in operation in both capitals are technically very similar, the difference is not only the track gauge (1435 mm vs. 1520 mm), but also, inter alia, the traffic safety system. Ensuring an adequate number of spare parts is also a major problem. In total, Warsaw metro operates 22 trains of the 81 series (15 of the old type and 7 of the new type), and the 10 oldest trains / 60 carriages of them would be sent to Kyiv, still in the first quarter of 2023. It has been agreed that the organisation of the transport of the metro carriages to Ukraine, including their insurance, is the responsibility of the Ukrainian party [36]. The first carriages of eastern production – the MMZ Mytishche plant near Moscow and Vagonmash from St. Petersburg – were delivered to Poland in the early 1990s in the number of 10 and 32 carriages in 1994, which, after the inauguration of the metro on the southern section of the 1st line (Politechnika – Kabaty) in April 1995 ran as 3-carriage trains (it was possible to put together 14 3-carriage trains). The adaptation of the carriages before sending them to Kyiv involves, among other things, the necessity to remove the equipment of the speed limit and radio communication system, event recorders, and others. It has been decided to donate the said carriages worth more than PLN 40 million free of charge [37]. These are trains numbered 01, 03, 04, 05, 06, 07, 08, 13, 14 and 15, with a mileage of 1.0-2.5 million kilometres, all of which have up-to-date certificates of technical worthiness and were last repaired between 2017 and 2022.

Fig. 26. The train 81 series at the Kabaty technical and holding station (STP) (23/09/2006) [photo: M. Graff]

[5] The idea of the Warsaw Metro authorities in preparation for the tender terms was the obligation to collect older rolling stock (i.e., series 81) by the manufacturer along with the deliveries of new trains. This idea was abandoned finally.

9. Extension of the Kabaty technical and holding station (STP)

In February 2020, the Warsaw Metro announced a tender for the design of the extended track layout of the Kabaty technical and holding station (STP) (Fig. 27), with the aim of ensuring smooth train traffic when there are more trains running. The objectives of the reconstruction are as follows [38]:

- increased number of tracks to allow trains to turn around,
- more efficient departure of trains from the Kabaty technical and holding station (STP) on the 1st metro line thanks to additional switches.

Fig. 27. The Kabaty technical and holding station (STP) (23/09/2006) [photo: M. Graff]

The objective of the reconstruction is also to reduce the time required for the various activities while maintaining traffic flow. At present, there are 4 tracks at the Kabaty technical and holding station (STP):

- the track no. 1 (east) – with retaining buffer stop, used as tunnel reserve,
- the track no. 2 (western) – exit to/from the Kabaty technical and holding station (STP),
- the tracks nos. 3 and 4 (central) – exit to/from the Kabaty technical and holding station (STP), and also for turning.

The system is slowly running out of trafficability performance, which is particularly noticeable at peak times, even though, it has to be said, it has been designed to accommodate traffic on one line and now serves practically 2 lines. So the plan is to reconstruct it, possibly installing new buffer stops:

- the track no. 1 and the track no. 3 would be connected at the end of the side tracks, allowing the track no. 1 is to be used as an exit from the technical and holding station (STP),
- the tracks nos. 2 and 4 would also be connected, so it would be possible to turn around on the track no. 2.

The potential reconstruction included obligatory:

- removal of part of the track or ballast-free tracks,
- demolition of a retaining wall,
- dismantling of the ceiling and tunnel support at the entrance to the tunnel.

The tenderer of the designer and at the same time the construction contractor) was also required to obtain all permits/authorisations (including the environmental one) and to supervise the investment, with 22 months allocated for the whole project, including the design of the reconstruction. The only selection criterion was the price.

10. The perspective of the construction of the Plac Konstytucji and Muranów stations

In December 2022, the metro authorities presented the main design assumptions for the two stations on the 1st metro line that have not yet been constructed (mainly for economic reasons) [39]:

- A12 Plac Konstytucji (between the A11 Politechnika and A13 Centrum stations),
- A16 Muranów (between the A15 Ratusz and A17 Dworzec Gdański stations).

The objective of the construction of the two stations has been to reduce the distance between the existing stations A11 – A13 and A15 – A17 from 1.5 km, with the average distance between stations for the Downtown area to be 0.8-0.9 km to ensure passenger service by metro in the area. Stations can be located:

- A12 Plac Konstytucji – between ul. Wilcza and pl. Konstytucji, the two-storey station with 2 post rows, three-aisle construction; station entrance/exit via stairs, no exits to the tram stops;
- A16 Muranów – between ul. Anielewicza and al. Andersa, a similar arrangement, as in the case of the A12.

The construction of the station should not interfere with the current traffic on the 1st metro line, it will therefore be necessary to:

- construction of a third tunnel between the Politechnika and Centrum and Ratusz and Dworzec Gdański stations, through which traffic would be routed during the construction of the A12 and A16 stations;
- adopting a similar solution would require driving on the wrong track during the closure of one of the

existing tunnels, which is not possible at present due to the nature of the traffic safety system installed on the 1st metro line;
- organisation of 2 to 6 construction sites, which would allow the construction of turnouts with connections between tunnels and a chamber for the TBM;
- adjusting the track layout and traffic on the 1st line:
  - permitting a passage between the road tracks at the A13 Centrum station for passenger traffic (towards the A14 Świętokrzyska station),
  - reconstruction of the connection of the side tracks located south of the A11 Politechnika station with the track no. 2,
  - reconstruction of the turnout at the A15 Ratusz station to ensure a passage from the track no. 1 to the track no. 2 without the need to change the direction of travel.

The construction of the station would be carried out using the floor method, along the axis of the platform, initially for one track (traffic would be routed on the second track), and when completed there would be a change (construction of the second platform, and traffic would be routed on the first track). This would involve the introduction of two-way traffic, so there would have to be a reduction in frequency, which also determines the construction time - the holiday period and 2 months (September and October). Construction would be carried out in 6 stages (table 12).

The shutdown of each tunnel will take an initial 13 months. Three implementation options have been considered:
- parallel construction of the A12 and A16 stations,
- construction of the A12, after the completion of the A16,
- construction of the A16, after the completion of the A12.

The 3rd option has been considered the most advantageous, because with the closure of one track in two sections, with a frequency of 10 minutes on each track, a shuttle train would run every 20 minutes or so. Moreover, until the construction of the technical and holding station (STP) of the Karolin station, the 2nd line would use the facilities of the 1st line (access, stationing of rolling stock at the Kabaty technical and holding station (STP)), so the construction of the A16 Muranów station in the first place is the optimum option from an organisational or traffic point of view. The design work, construction approvals, and environmental decision should be completed by the end of December 2023, with a construction time of about 3 years for each station. To maintain the current frequency, the addition of another train is required after the completion of the A12 and A16.

11. Number of metro passengers

Since the inauguration of the metro in 1995 and the commissioning of successive sections, the number of metro passengers in Warsaw has been gradually increasing (Fig. 28). In 2008, after the commissioning of the last section of the 1st line and at the same time before the inauguration of traffic on the 2nd line in 2014, the number of passengers stabilised at 140-150 million per year. With the inauguration of the 2nd line and the commissioning of further sections, once passenger numbers had increased to around 200 million per year, growth was less, with a trend towards stabilisation at 230–240 million. The SARS-Cov-2

Table 12

Characteristics of potential construction of the Plac Konstytucji and Muranów stations [39]

Stage	Description of the investment works	Time [months]
1	preparatory work, elimination of collisions	4
2	construction of underground passageways on the eastern side and temporary tram trackage	9
3	construction of 3 slurry walls in the western and central aisles, as well as the ceiling over the western aisle and stairs to the underground passageways on the western side	6
4	construction of the station body: slurry walls in the eastern and transverse aisles and the remaining part of the ceiling*	8
5	construction of the station on the west side (analogous to the 4th stage), train traffic will be carried out in the east tunnel*	8
6	installation and finishing works	3

* During the construction of the station in the 4th / 5th stage, the existing east / west tunnel would be closed and the section overlapping with the new station reconstructed – the tunnel tubes and equipment in the tunnel would be dismantled and the substructure, tunnel floor, congestion walls and platform would be constructed.

coronavirus pandemic that started in Europe around March 2020 and the associated restrictions: the need to cover one's face with a mask, distance oneself from other people in public places, including public transport, and the prevalence of remote working caused passenger numbers to fall to approx. 170 million.

Data for 2022 is not yet available, which will take into account the increase in passenger numbers caused by the commissioning of new sections running through multi-family housing estates, as well as the lifting of pandemic restrictions from the first half of 2021 caused by the start of a widespread vaccination campaign against SARS-Cov-2 in EU countries, including Poland. However, it should be assumed that a similar increase may be smaller than, for example, for the 1st line in a similar period, due to the spread of remote working, which means, among other things, lower occupancy on public transport, including the metro.

Table 13 shows the number of passengers using each station. The information has been obtained from the Passenger Counters at the gates of the Fare Collection System (FPS) and the Passenger Counting System (PMS) at the connector between the M1 and M2 lines. On the other hand, the estimated number indicates the number of passengers transported taking into account:

- data from counters at the ticket gates and from passengers using lifts,
- those jumping over the ticket gates,
- using the link between the M1 and M2 metro lines,
- the vast majority of passengers use the emergency exits on the M1 metro line.

The stations with the highest number of passengers (according to the FPS) on the 1st line are Świętokrzyska, Politechnika, Centrum and Ratusz Arsenał (8.5–12.5 million passengers), located in the very centre of the City, the first of which is an interchange station with the 2nd line, and the Wilanowska station located at the interchange centre, as is the Młociny station (6.4 million), possibly in the city centre – the Wierzbno and Pole Mokotowskie stations (~6 million). Further stations are located within housing estates with multi-family buildings: Kabaty, Służew, Imielin, Natolin and Stokłosy (southern section of the 1st line), possibly near a railway station (Dworzec Gdański), with passenger numbers of 4.6–5.8 million. Another group of stations with the lowest number of passengers are mostly stations located on the northern section of the 1st line – Wawrzyszew, Wilson Square, Marymont, Słodowiec and Stare Bielany, with 2.2–3.7 million passengers. On the other hand, on the 2nd line the attendance is definitely lower in comparison to the 1st line, except for the Świętokrzyska station (12.5 million) and fluctuates within the range of 6.6-8.5 million for the Dworzec Wileński and Rondo Daszyńskiego stations or 2.7–4.6 million for the stations: Rondo ONZ, Nowy Świat – Uniwersytet, Stadion Narodowy and Centrum Nauki Kopernik, are located in the central section of the 2nd line. The number of passengers at the remaining stations does not exceed 1.1 million (Trocka, Targówek Mieszkaniowy and Szwedzka)[6] and these are stations located on the then-newly opened section in the eastern part of the 2nd metro line. Similar data (daily occupancy for selected stations) is presented in Table 14.

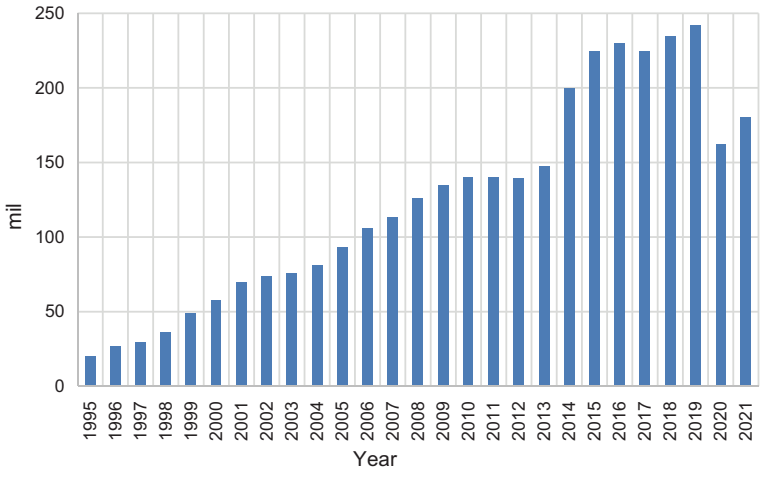

Fig. 28. The number of passengers on the metro in Warsaw over the period 1995–2021 [31]

[6] The stations are located in one of the poorer parts of Warsaw, so the lower standard of living reduces the mobility of a significant part of the population.

It is worth noting the high number of passengers using the new Bemowo and Kondratowicza stations, located respectively on the western and north-eastern sections of the 2nd line, which should be explained by the location of both stations within large housing estates.

Analysing the data from Table 13 in terms of the estimated number of passengers, it can be seen that on the 1st line significantly more people do not use, inter alia, the ticket gates compared to the 2nd line (22% vs. 1%), with as many as half of the passengers at the Centrum station. High values are also obtained for stations: Wilanowska, Wierzbno, Racławicka and Pole Mokotowskie. On the 2nd line – due to the different design of the ticket gates, jumping over them is virtually impossible.

Table 13

Annual statistics of metro passengers in 2019 [40]

Lines	Designation of stations	Station	Number of passengers using the metro [mil]		
			according to the FPS (A)	estimative (B)	(B – A)/A·100%
M1	**A1**	Kabaty	5.75	5.93	3.1
	A2	Natolin	4.75	4.88	2.7
	A3	Imielin	5.13	5.23	1.9
	A4	Stokłosy	4.59	4.69	2.2
	A5	Ursynów	3.36	3.46	3.0
	A6	Służew	5.59	6.88	23.1
	A7	Wilanowska	8.43	11.01	30.6
	A8	Wierzbno	6.11	9.40	53.8
	A9	Racławicka	3.68	4.83	31.3
	A10	Pole Mokotowskie	5.88	8.08	37.4
	A11	Politechnika	11.65	13.22	13.5
	A13	Centrum	9.96	19.79	98.7
	A14	Świętokrzyska	12.62	12.96	2.7
	A15	Ratusz Arsenał	8.99	9.75	8.5
	A17	Dworzec Gdański	5.27	5.84	10.8
	A18	Plac Wilsona	3.24	3.89	20.1
	A19	Marymont	3.13	3.28	4.8
	A20	Słodowiec	3.11	3.23	3.9
	A21	Stare Bielany	2.19	2.26	3.2
	A22	Wawrzyszew	3.67	3.75	2.2
	A23	Młociny	6.37	8.11	27.3
		In total for the M1	**123.47**	**150.47**	**21.9**
M2	**C09**	Rondo Daszyńskiego	6.64	6.7	0.9
	C10	Rondo ONZ	4.60	4.64	0.9
	C11	Świętokrzyska	12.49	12.54	0.4
	C12	Nowy Świat – Uniwersytet	4.59	4.65	1.3
	C13	Centrum Nauki Kopernik	2.72	2.76	1.5
	C14	Stadion Narodowy	3.15	3.19	1.3
	C15	Dworzec Wileński	8.46	8.56	1.2
	C16	Szwedzka	0.24	0.24	0.0
	C17	Targówek Mieszkaniowy	0.49	0.49	0.0
	C18	Trocka	1.12	1.12	0.0
M1 and M2	**In total for the M2**		**44.5**	**44.89**	**0.9**
	In total for the M1 and M2		**167.97**	**195.36**	**16.3**

Table 14

Daily statistics of metro passengers [41]

Lines	People entering [thousands]	People leaving [thousands]
First	393.2–415.0	388.9–418.0
Second	241.0–261.5	253.7–271.3
Stations	**People entering (on average)**	**People leaving (on average)**
Centrum	43 697	47 281
Politechnika	40 569	39 987
Młociny	26 498	N/A
Ratusz	N/A	24 359
Dworzec Wileński	25 109	27 573
Rondo Daszyńskiego	21 993	22 142
Rondo ONZ	21 724	22 661
Świętokrzyska connector / gates	31 040 / 18 389	26 815 / 23 171
Bemowo	14 664	20 188
Kondratowicza	13 538	11 781
Bródno	8219	8762
Ulrychów	5751	6757
Zacisze	2083	2097

12. Conclusions

The metro in Warsaw, which has been under construction for around 40 years with a near-target route, now consists of two lines, intersecting at one point. Despite difficult beginnings in the 1980s (economic crisis, no access to modern technology, etc.) the initial difficulties have been overcome and construction accelerated significantly in May 2004, after the accession of Poland to the EU. This meant, among other things, access to aid funds (Operational Programme Infrastructure and Environment), which have been earmarked not only for the construction of the line (e.g. purchase of TBM) or station equipment, but also for acquiring modern rolling stock. The acceleration of construction is evident when comparing the time years of construction of the 1st line (1983–2008) and the 2nd line (approximately 2009–2026), i.e. 25 years and 17 years, with a comparable length of both lines (approximately 20–22 km). Furthermore, it should be taken into account that the 2nd line is located at a greater depth than the 1st line, so construction was more difficult. The construction of the 2nd line has been considerably accelerated by the use of modern TBM, while the 1st line (southern and northern sections) has been constructed using the Milan method and the middle section has been constructed using the deep-cast method. The steadily increasing number of passengers shows that the urban railway in Warsaw has gained the appreciation of its inhabitants as well as visitors, including commuters from the suburbs.

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