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Abstract

Currently, Bratislava is experiencing massive development and great activity of developers. The city is expanding and acquiring much higher masses representing people in its down town. And these people are always moving. With the development of the city, it is necessary to place emphasis on the development of public transport. Public transport must be ecological, economical and accessible to all social groups of the population. In the conditions of Bratislava, the city has the opportunity to change the modal split in favour of public transport and thus end the decline from the early 90´s of the last century. Rail track transport is one of the ecological types of public transport and is part of smart cities in the area of serving the land use in cities. The current rail track public transport in Bratislava is covered by tramway and train infrastructure. Train transport ensures the relocation of people from the surrounding municipalities of Bratislava. Tramway transport ensures the relocation of people in the city. There is a need to connect the performance of tram and train PT. This affects the time length of the travelling of people. The foundations for the creation of a dual rail transport system in an urbanized area are prepared in Bratislava. The goal of the article is present the technical solution of double gauge system for operation and the traffic engineering and planning works for decision making. It was done a huge professional and expert works which one is against the political an administration "decision making". These experiences from Central Europe are presented.

Keywords: public transport, tram-train, traffic modeling, railway design.

1 Introduction

It is true that for economic reasons, the public transport lines cannot be introduced everywhere and therefore, when planning public transport lines, it is also necessary to consider transfers from one system to the second. For the passenger is an attractive public transport without transfers. In the case of Bratislava agglomeration, it is an empirical experience in the surrounding municipalities. And this is the reason why people don't want to use public transport and they are still using private cars. Even though they have a time lost staying in queues. In some cases, the possibility of removing transfers, and this can be ensuring at the rail track transit when transfer is on the platform edge to edge. The second way is to use the system of conveyance transport even for railway and urban tramways.

Many passengers use train transit to Bratislava for daily attendance. If passengers want to use tram transport, they must be transferred. And it takes couple of minutes or some hundreds of meters for

accessibility. The next disadvantage is to wait on the stop or platform for next link. In some cases, transferring can be removed by introducing a Tram-Train system or by building a tram intercity rail tracks to the surrounding municipalities of Bratislava.

In the world, there are experiences with agglomeration tram-train network from other cities in Germany or France. Economically advantageous is to use the connection of existing railway tracks on the existing tram network and introduce Tram-Train. It is a hybrid vehicle that can ride the railway infrastructure and after the urban tracks.

Tram-Train resembles a classic tramway. The widths of grooves in tram rails must also be taken into account, because tram-trains have railway wheels, which are a wider roadband. A smaller chassis distance for classic trams allows for arches with smaller radius as minimum radius on a classic railway line. Many detail, e.g. different vehicle widths (tram-train 2650 mm, tram 2500 mm), platform edges of stops, switches etc. All these details are technically solved for the Bratislava in all technical details in [1, 2]. Especially in Bratislava where we have a double track system because the narrow gauge 1000 mm for tramway and a normal gauge 1435 mm for tram-train.

The land operation issue also dealt with in [3, 4, 5, 6]. A significant benefit of so-called and often used „sustainable mobility“ is a change of modal split in favour of public transport. These analysis were published in [7, 8]. This is not only reached in the city's territory but also affects suburbanization of Bratislava city and its background min. up to 50 km away from city centre. The land operation principles of the public rail transport were defined in 2011 when the city asked State and the EU on the possibility of financing the project form EU funds [9]. Strategy and technical solution were defined by 2010 [2] and DG Transport in the EU at that time guided the city of Bratislava that possible within sustainable transport and the public transport development system to link the Main railway station through the city center and the river Danube towards Austria and Hungary. It will be a significant cross-border project among the three states and in particular a sustainable way to ensure the operation of Bratislava at the same time with its agglomeration.

2 Strategy of network development of tram-train in Bratislava

Throughout the area of the Capital of Slovak Republic Bratislava there are 80 km of rail tracks of 1435 mm gauge, which uses the railway. Not all are in operation. According to the processed technical and economic study [1], they were examined and defined conditions for:

- design and implementation of transport infrastructure of railway and trams in parallel operation,
- suitable type of „designed vehicle“,
- risks and uncertainty resulting from design, implementation and operation of transport infrastructure for common operation of rail and tramway vehicles,
- estimate of investment and operating costs,
- assessment the economic parameters of the construction.

Basic conditions for the development of conceptual, transportation, operational, building and technical solution were based on the assignment with these operating conditions:

- Permanent railway vehicle - train (tram-train) will be built within construction of „linking corridors“ with train lines from Petržalka:
  - through railway station Bratislava - Filialka (nowadays studied) to railway station Bratislava - Predmestie followed the possibility of continuing direction to the region (Raca borough, Pezinok, Trnava) or
  - direction railway station Bratislava - Nové Mesto borough, Podunajske Biskupice borough, Dunajska Streda,
  - or direction Vajnory borough, Galanta, Nove Zamky (this is a complete background of

Bratislava agglomeration).

- In the opposite direction from railway station Petržalka with the possibility of getting to Austria and Hungary.

The permanent transit operation simultaneously tramway and railway coach (train) in the study described as „dual operation“ where the tram –train vehicle is involved in surface trams network in the city.

The proposed transit rail infrastructure reflected into construction objects and operational frameworks. The operation of rail and tram track rolling stock must comply with these basic (characteristic) technical parameters for:

Tramway track

- Gauge: 1000 mm,
- Height of the boarding edge above the railhead is max. 300 mm,
- Traction Power System: 750 V DC (at current lines 600 V DC),
- In sections of common (railway) infrastructure: design of direction and high-rise route (rail track) must comply with [XX - TNŽ 73 6361 Geometric position and track arrangement of 1000 mm gauge track tracks],
- In sections outside the common (railway) infrastructure, standard [STN 73 6405 - Designing of tramway tracks] can be used.

Railway Track:

- Gauge: 1435 mm,
- Traction Power System: single-phase 25 kV / 50 Hz AC,
- Height of the boarding edge above the railhead is max. 550 mm with sliding step in floor level for railway platforms, on the tram stops inside the city the coach will have a step for 300 mm
- Max. axle pressure: 18 t (after the testing of producers of trains for tram-train was defined for 12,5 t),
- Min. arc radius: 300 m,
- Platform length 80 m (120 m for selected stations), inside of city on tram stops max. 70 m
- Track speed 80 $km.h^{-1}$
- Cross section UIC-C
- Station and track security devices with lightweights,
- Track equipped with ERTMS (ETCS LEVEL) 2, GSM-R),
- design of direction and high-rise route must comply with [STN 73 6360].

The aim of [1] was to define a recommended technical solution while establishing economic parameters of infrastructure structures for the emergence of a modern integrated rail track transport system with the use of a common infrastructure railway and tramway pathway. The study demonstrated that transport technology and economic evaluation respects the requirement for a technical modern solution and reality of construction for all affected structure objects (track bottom, upper, solid traction equipment, railway security devices, notification equipment, stops, platforms) so that comply with applicable technical conditions, regulations and standards. In addition, the infrastructure will serve at the same time the railway and tramway (dual system), and so the structure objects concerned must meet the technical conditions for both pathway systems. The time horizon of the start of each pathway may not be identical. Very detailed all relevant details for different track gauge (1435 versus 1000 mm) were dealt with, relationship analysis between „rail – wheel“ and dual operation itself.

2.1 Modal split problem: Personal dynamic car traffic and modal split

To estimate the probable benefit for public transport (PT) in modal split, especially for rail track PT represented by dual gauge tramway and tram-train operation a huge traffic survey and uni-modal traffic model was created according [10, 11]. The quick results are shown below. The aim was to declare the quantity of passengers possible to use the Carrying Public Transport System (CPTS) which is defined for Bratislava by rail track infrastructure in [12].

What is important for the model was used the BUS line network in Petržalka borough without any change. So it means the ADT value of passengers for bus PT keep the modal split value also for the future scenarios.

Dynamic car transport development in Petržalka borough has an unsatisfactory trend mainly on the bridges connecting the left and right bank of the Danube. In passenger transport, it is constantly increasing population mobility - minimum increases the average number of routes per day/inhabitant, on the contrary, the length of the journey is growing significantly). However, with a trend of continuous growth of cars, the problem of territory is increased. Without the CPTS Petržalka borough will collapse.

Modelling various scenarios pointed that the construction of other zone units in Petržalka - Petržalka City, Matador, Southern City, New Lido will bring together additional 42 000 inhabitants and 40 000 employment opportunities. According to [9], it was mentioned that in 2020 without CPTS public investment on the bridges through the Danube causes a tremendous collapse. Data is in Table 1. Currently, in 2020 (before the pandemy rules – till beginning of March), it is truly notes that filling the capacity of all bridges through the Danube achieves LoS (Level of Service) E-F saturation volumes at rush hours. In this traffic model was not included the first phase of the tramway link toward Petržalka which in in operation from 2015 with only three stops on the side of Petržalka. Traffic volumes on bridges are found in Figure 1. In the next Figure 2 the scenario with investments, but without CPTS to the south of Petržalka, shows the complete traffic volumes of bridges, but using CPTS between Petržalka and the city of Bratislava through the Old Bridge. Traffic volumes of bridges with CPTS are in Table 2. Values difference of average daily traffic flow and peak hours are in Table 3.

Figure. 2 Max traffic peak (veh/h) on bridges for 2020 without investments and CPTS [10]

Figure 1 Max traffic peak (veh/h) on bridges for 2020 with CPTS [10]

The output form the traffic model shows that the saving number of vehicles is up to 57,000 vehicles in 24 hours (difference from Table 2 and 3) in the average working day. Values are shown in Table 3. These values are the possible passengers for CPTS in modal split for tramway without any resistance functions in the traffic model. According the [28] the personal car occupancy in Bratislava is 1.2 pass / veh. With simple degree of resistance for model we can use -20% or more up to -30% of ADT for calculation of PT passengers. And this account is used only for the tramway track in south direction of Petržalka in the middle of the borough with 110 000 inhabitants living there and not for the tram-train link to the railway station Petržalka.

After resolving the technical and technology details, the city of Bratislava could start to implement the dual gauge with a tram network of 1000 mm and normal gauge 1435 mm for tram-train. The basic strategy of CPTS operation was approved by the Ministry of Transport and Construction of the Slovak Republic as well as the EU DG Move and Jaspers institutions in 2012.

Table 1. Average daily and peak traffic volumes for 2020 without CPTS on Danube bridges

	2020 (ADT veh/24h)			PeakHT-MAX (veh/h)			PeakHT – 50thh (veh/h)		
Danube bridge	Direction 1	Direction 3	Profile	Direction 1	Direction 3	Profile	Direction 1	Direction 3	Profile
Lafranconi	34 980	34 670	69 650	4 520	4 520	9 040	3 680	3 670	7 350
SNP	35 220	35 280	70 500	4 320	4 470	8 790	3 700	3 550	7 250
Apollo	26 580	26 470	53 050	5 150	4 360	9 510	4 220	3 780	8 000
Port	45 830	45 270	91 100	4 520	4 800	9 320	3 830	4 280	8 110
Sum	**142 610**	**141 690**	**284 300**	**18 510**	**18 150**	**36 660**	**15 430**	**15 280**	**30 710**

Table 2. – Average daily and peak traffic volumes for 2020 with investments and CPTS

	2020 (ADT veh/24h)			PeakHT-MAX (veh/h)			PeakHT – 50thh (veh/h)		
Danube bridge	Direction 1	Direction 3	Profile	Direction 1	Direction 3	Profile	Direction 1	Direction 3	Profile
Lafranconi	25 900	28 770	54 670	3 770	3 350	7 120	3 020	2 700	5 720
SNP	27 280	28 880	56 160	3 380	3 690	7 070	2 880	2 910	5 790
Apollo	20 500	22 360	42 860	3 960	3 720	7 680	3 240	3 240	6 480
Port	35 700	38 010	73 710	3 540	4 010	7 550	2 990	3 590	6 580
Sum	**109 380**	**118 020**	**227 400**	**14 650**	**14 770**	**29 420**	**12 130**	**12 440**	**24 570**

Table 3. - Difference of transport intensity values

	2020 (ADT veh/24h)			PeakHT-MAX (veh/h)			PeakHT – 50thh (veh/h)		
Difference	**33 230**	**23 670**	**56 900**	**3 860**	**3 380**	**7 240**	**3 300**	**2 840**	**6 140**

In Bratislava, the possibility of using the built dual gauge from the city center in the section from Sturova Street (in down town) towards a reconstructed Old Bridge up to Jungmannova Street in Petržalka, where is already the infrastructure in a dual gauge with rails with wide groove for railway wheels for 1435 mm gauge and rails for tramways wheels for 1000 mm in length 2.4 km. This construction was completed in 2015. Since 2014, after changing the city management and after political (not a professional) decision from the level of the city with the support of the Ministry of Transport, the state and municipality administration stopped the work of dual system. Moreover, after changing the team in the EU institutions in Brussels and these experts from DG Move and Jaspers did not contribute to continue the modern and meaningful project of integrated rail transport. The original feasibility studies [1, 2], which have resolved in detail the technical and economic attributes declared clearly:

- Multiple connection of the individual radials of railway lines entering the city to create
- Ability to link integrated rail transport on the tram track network using the tram-train double-feed vehicle, also operate them on the railway infrastructure and thus guarantee
- Necessity of requirements for the implementation of the subsurface North - South interconnection at the future Filialka Railway Station.

The Tram-Train Scheme network and its operation of the city and the agglomeration is shown in Figure 3 according [3]. Black double lines are the main railway infrastructure directions, blue lines are present tramway lines, red – trolleybuses. The future network of tram-train is orange lines which ones could be directly follow – connect the railway infrastructure.

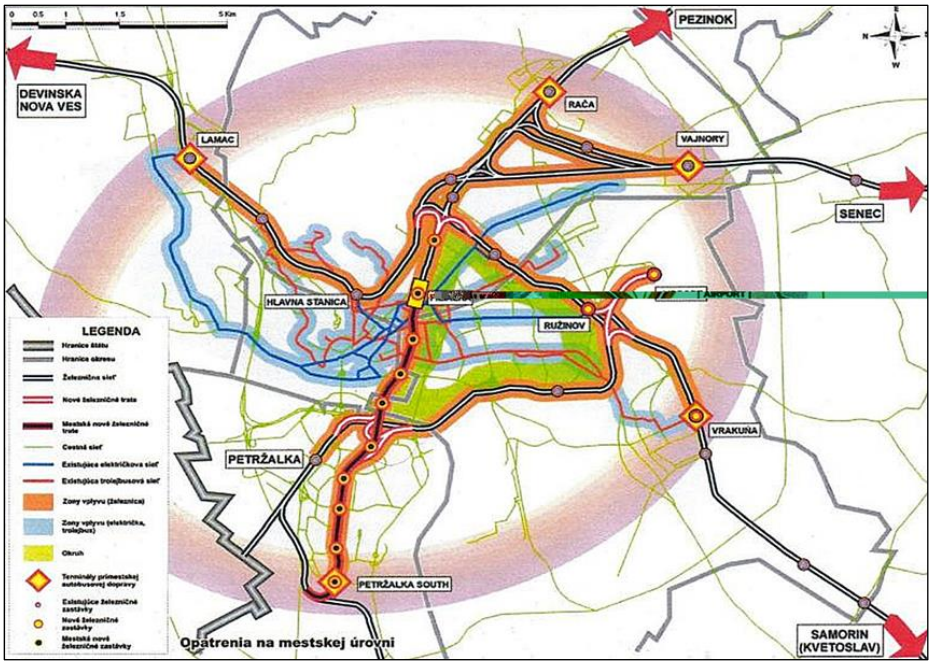

Figure 3. Strategy and principles of main directions and circled of integrated rail transport in the territory of Bratislava [3]

3 Proposed tram-train route for the Filialka - Petrzalka project

The basic document of the study Upper bridge Einsteinova street, prepared by the design company [13], was used to design the tram-train route from the Petržalka railway station. This project solves the construction of a large plateau with new functions for the Digital Park shopping center and administration and the Aupark multifunctional shopping center. The original design of the study is shown in Figure 4 [13].

The proposed route for the tram-train is connected to the newly built tram line with a dual gauge in the city part of Petržalka in the embankment body in front of the flyover over the D1-motorway on Einsteinova Street behind the Old Bridge. The track for the tram-train is on the proposed plateau above the D1 motorway on Einsteinova street. Tram - train stops are proposed behind the Digital park building. The route continues along the ramp below the road overpass and is connected to the existing

Petržalka railway station. The proposed track for the tram-train is in a modified situation plateau above Einsteinova Street in Fig. 4. On Fig. 5 is also the situation of the Petržalka railway station [14].

Figure 4. Design of a tram-train route (red colour) on the plateau over Einsteinova street to the Petržalka railway station

From the Old Bridge with the existence of a dual gauge is possible to continue with the tram-train route to the existing Filiálka railway station. The renewal of the Bratislava - Filiálka railway station in the northern part of the city center of Bratislava is also planned. This station will be used only for regional rail transport of the Slovak railways [15]. The interchange node Filialka is the subject of further detailed proposals and their basic idea is to create a connection between the existing underpass on Trnavske Myto for people for the PT terminal and the future underground railway station Filiálka. This will create a connection to the tram PT. The moving from the underground rail station to the tram (tram-train) would be in the underground and does not collide with surface road transport. City bus a trolleybus PT will be located closer to the underground station. This interchange node should be of state and regional importance, providing a transfer between external rail transport and urban public transport [2].

4 Connection of the tram-train route to the Petrzalka railway station

The connection of the tram - train is on the ladder track towards the Bratislava ÚNS railway station. The schematic situation of the railway station Petržalka is ion Fig. 5. The tram train route is in the design connected to tracks no. 6 and 8, for an even group of tracks. At present, the even group of tracks towards the Bratislava railway station ÚNS is connected by simple switches of the type S49 1: 9-300. These are the switches no. 14, 15, 17 on Fig 5. One of the technical solutions for connecting the tram-train route to the tracks no. 6 and no. 8 is a replacement the switch no. 14 and switch no. 15 for simple switch of the type S49 1: 11-300 and replacement the switch no. 17 for the double crossing switch of the type S49 1: 11-300. In the track no. 8 will be inserted a new simple switch of the type S49 1: 11-300. The reason for replacing these switches no. 14 and no. 15 in this ladder track is that the double crossing switch is only of type 1: 11-300 and the angles of the turnouts should be the same. It is also necessary to connect the tram-train track to the track group no. 1 to 15. Railway connection between parallel tracks is necessary. To make it possible, it is necessary to unify the ladder tracks in to the odd group of tracks no. 1 to 15. The reason is to obtain more space for inserting railway bonding between parallel tracks. Switches are often used on railway lines and can also be found in some turnout catalogues [16, 17, 18]. There are more technical possibilities of connecting tram-train tracks. The tram train will stop at the platform no. 1. On the Figure 5 is the scheme of the connection of tracks for tram-train to the Petržalka railway station.

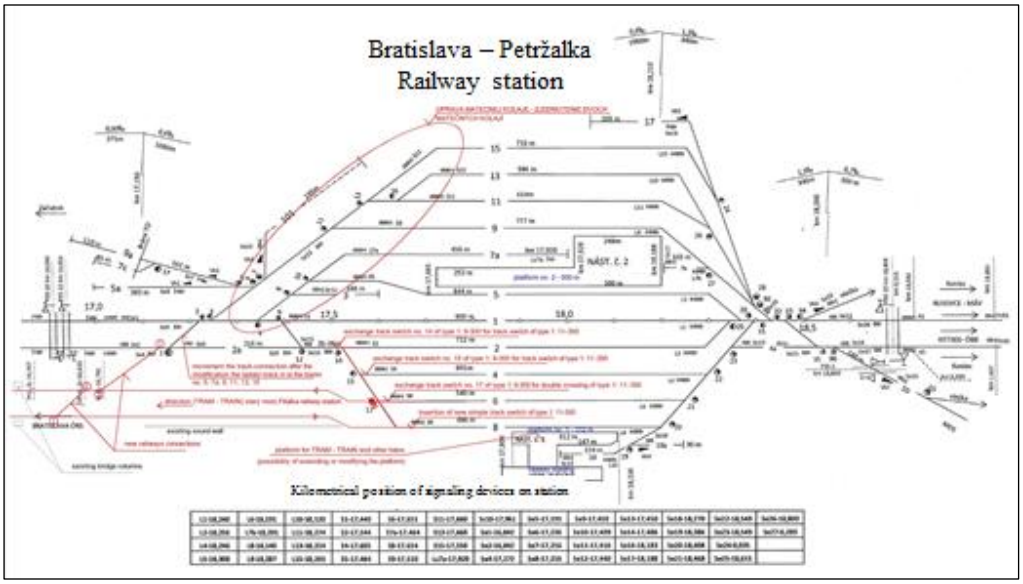

Figure 5. Scheme of connection of tracks for tram-train in the Petrzalka station [7]

5 Transport model scenario of modal split for new tram - train line route

Part of the proposal of the tram - train track is also the assessment of public transport in the urban transport model. In general, the macroscopic transport model is used to solve the optimal scenario of

the transport system of a city or region development. The main purpose of the transport model is to analyse the current problems in transport and to predict the future state of service in the area [19, 20]. The generel systematic issue of the integrated public transport system was used from [21]. Philosophy of nods –railway stations and PT stops were compared from the rules according to [22]. Macroscopic transport models are often used as a tool to qualify various projects and find the most appropriate solution to solve transport problems.

The traffic model of Bratislava city and its region is processed in the transport planning software PTV VISUM [23]. The design of zonal structure of the transport model is based on definition of territory for the transport model and consists of internal and external zones (so - called external). These zones serve as origins and destinations for journeys made within one day (or part of a day). The area of the capital city of Bratislava has 263 internal zones in the transport model, which correspond to the basic settlement units.

The external zones include the municipalities of the catchment area of the capital and further aggregated municipalities of more distant areas. In Slovakia, the model covers the entire Bratislava and Trnava regions - which represent 347 zones. The model also includes 16 zones from Austria (part of Lower Austria and Burgenland) and 5 from Hungary (Moson). At the edges of the region, the model enters / exits traffic using the so-called cordon zones. Fig. 6 represents the model area of the transport model of the city of Bratislava according to [24], which was modified and changed according to the principles of [25] for the solved new city center.

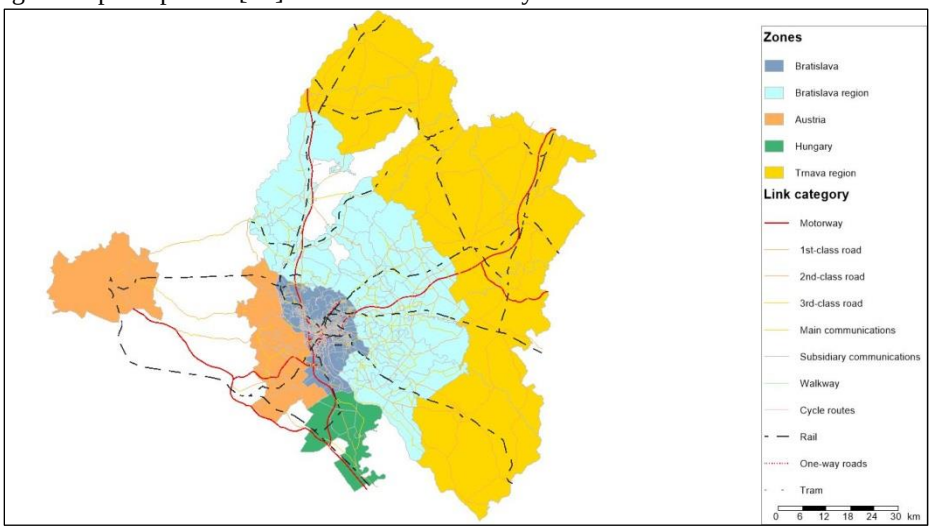

Figure 6. Model area of the transport model of the city of Bratislava in the territory of the agglomerations Vienna – Bratislava in PTV VISUM

A new line in the direction of Raca - ŽST Petrzalka was created in the transport model of the city of Bratislava for the needs of the proposed line route. This line route copies the line route to Petržalka, while the continuation of this line is also shown in Fig. 7.

There will be two stops on the proposed line route (see Fig. 4): Aupark (tram) and Dvory (tram) and the final stop is directly at the Petržalka railway station (ŽST Petržalka). Distance between stops:

- Sad J. Kráľa - Aupark (tram) - 990 m,
- Aupark (tram) - Dvory (tram) - 370 m,
- Dvory (tram) - Petržalka Railway Station - 860 m.

The scheme of proposed stops as well as the line route as an output form traffic model of public transport is shown in Fig. 8.

After designing new tram line route and stops, the transport model was re-calculated. The result is a cartogram of the volume of passengers transported on the tram line during the average working day. This scenario was put inside of uni-modal PT model. The maximum volume of transported passengers on the new tram line is in the section between Sad J. Krala and Aupark (tram) and represents in the profile section up to 18,847 transported passengers in 24 hours. The cartogram of the volume of the passengers is shown in Fig. 8. Fig. 8 also shows the number of boarding and alighting passengers at individual stops in the form of a bar graph (blue colour - boarding, green colour - alighting).

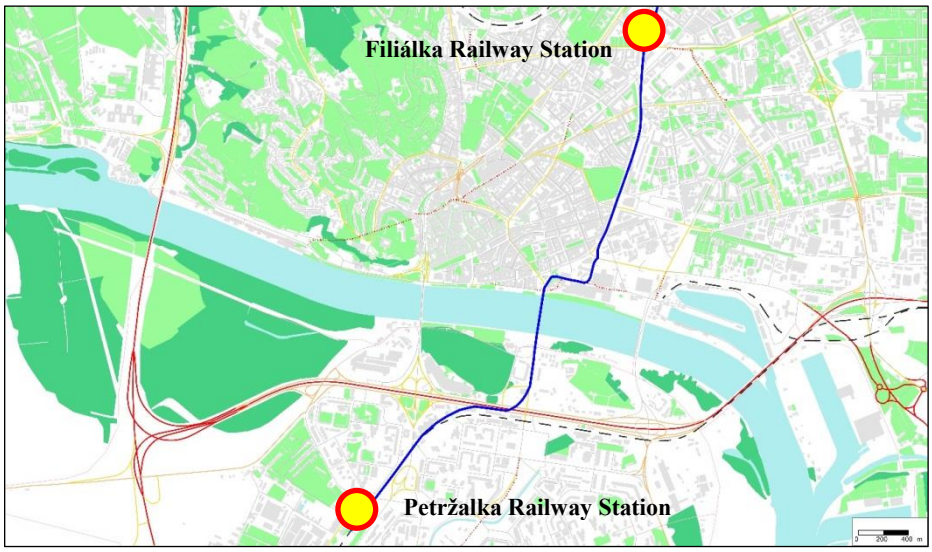

Figure 7. Scheme of planned tram - train line route (blue colour) in PTV VISUM

Figure 8. Flow map of transported passengers by planned tram – train line [pass./24h] between two railway stations in PTV VISUM

Fig. 9 represents a cartogram of transported passengers of the tram line network on an average working day in the monitored area on the side of Bratislava. The schematic output is form the city public transport model. Very interesting are the volumes on the stops of tram-train in the city network.

These are in Table 4. The numbers are very high and this could be the point of qualified decision making for the municipality of the City Bratislava.

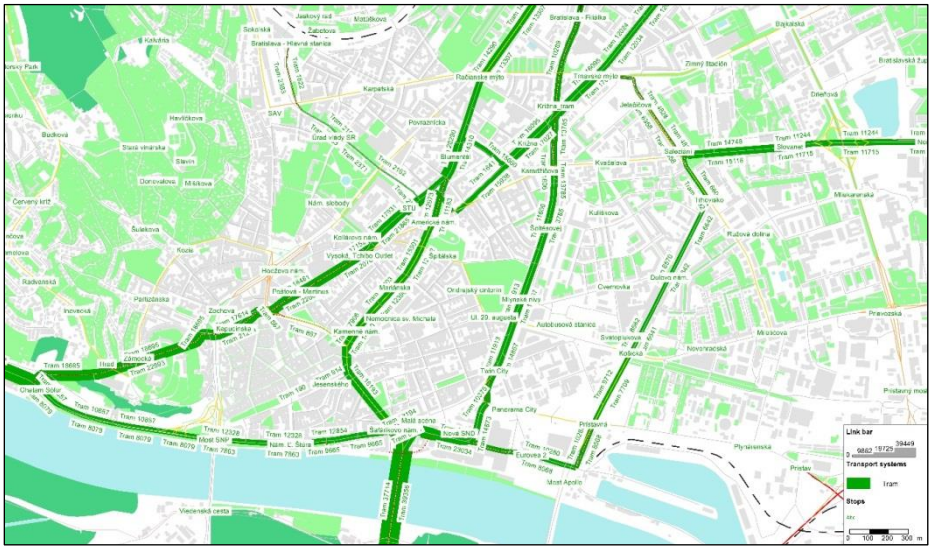

Figure 9. Flow map of transported passengers by tram in monitored area [pass./24 h.] in PTV VISUM

Table 4. Passenger volume on tram – train line between Petržalka – Filialka Railway stations

Public transport stop	Volume of passengers (pass./24 h.)	Boarding (pass./24 h.)	Alightning (pass./24 h.)	Volume to (os./24 hod.)	Volume from (os./24 hod.)	Cross - section volume (pass./24 h.)
ŽST Petržalka	12578	6220	6358	6220	6358	12578
Dvory (tram)	2991	2174	817	8214	6995	15209
Aupark (tram)	4028	2058	1970	9987	8680	18667
Sad Janka Kráľa (profile Starý most)	20607	10304	10303	39356	37714	77070
SND (profile Olejkárska)	13314	6675	6639	14873	10375	25248
Twin City	9390	3918	5472	14857	11913	26770
Mlynské Nivy	5532	2482	3050	14234	11858	26092
Šoltésovej	3353	1578	1775	13785	11606	25391
Krížna (tram)	7563	3716	3847	12337	10289	22626
Bratislava - filiálka	3829	1847	1982			

6 Conclusions

In the long-term preparation of technical studies for the development of urban rail transport in Bratislava, a systemic proposal for a solution on how to develop a modern system of surface rail public transport in the Bratislava agglomeration was professionally developed. If we really want to address the sustainability of mobility and change the modal split in favour of public transport, there is no other option. Moreover, accessibility in the Bratislava conurbation is around 30 km from the city centre. The population density is not high, so the development of an underground urban railway cannot be considered in a generational and long-term perspective. On the other hand, the specificity of the city of Bratislava in the narrow gauge of 1000 mm limits of the tramway network and the quality in terms of operation as well as durability of the entire supporting system of public transport, which is defined in strategic documents in rail traction. The principle for the use of low-floor tram vehicles in the conditions of Bratislava is also determined by the vehicle width, which is 2500 mm. and thus the basic physical laws are given, which are reflected in the economics of the transport system. This is reflected in the operation, maintenance, repairs and especially in the quality of the technical and technological system of the public transport itself. In addition, the existing rail network of the national railways as well as abandoned lines can be used in the agglomeration. It is also possible to deal with the dual gauge, the germ of which exists in the city and, in addition, the new bridge crosses the Danube River. However, development in the city is stalled precisely because of too much weight on losing political solutions that ignore appropriate engineering and technical proposals. However, the example also of this paper, which is available in the background of the technical-engineering work, speaks of a possibly strategic development of the city area.

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