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Original Article

TRAM-TRAIN SYSTEM AS A POTENTIAL TRANSPORT SOLUTION FOR THE OLOMOUC REGION

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Highlights:

- because of its specific requirements and vehicle purchase costs, the tram-train system has been applied in different forms across Europe and has to be sound in comparison to conventional railway or suburban tram alternatives;
- the Olomouc Urban Agglomeration is suitable for a tram-train system introduction by having a suitable tram network and several unattractive regional railway lines with an urgent need of modernisation;
- the proposed tram-train system utilises its specific advantages by reaching the coverage of the local bus lines with the door-to-door travel time of the express bus lines with less infrastructure needed than the conventional railway;
- from the variety of possible technical combinations, the low-floor dual-voltage vehicles in suburban configuration as an integral part of the regional transportation grid are recommended;
- with different stages according to the chosen operational extent, the Olomouc tram-train system with suitable configuration can be a game-changer for the commuters without the need to built complicated urban infrastructure.

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Abstract. The article is focused on the frequently discussed topic of suburban and regional railway system modernization comparing different approaches to consider by local authorities. To make a precedent and to better contribute to practical problems, a middle-sized city of Olomouc (Czechia) is chosen to demonstrate the upgraded regional transport system design with respect to the regional specifics and utilizing of the current railway and tramway infrastructure. With a new, innovative approach to the potential tram-train implementation in the Olomouc Region, the technical and operational features of the current tram-train systems and vehicles are analysed. By implementing the most suitable ones, the regional tram-train system proposal in the conditions of Olomouc may serve as a guide for similar planned systems in the countries with limited legislative and technical experience regarding the tram-train systems (especially in Central Europe), their suitability for the region, their design, and introduction. For the qualitative assessment of the different relevant approaches, a comparative analysis is used. As a result of the analysis, a tram-train system is recommended for the further transport planning stages as it significantly improves both urban and suburban public transport in the Olomouc Region by increasing their average speed and accessibility. For better financial and technical implementation, the project is divided into several stages. Unlike the already presented solutions, it combines shorter travel times of the regional rail and the populated area coverage reached by regional buses and serves as both an attractive and financially sane extension of a regional public transport system.

Keywords: modal split, public transport, regional railway network, railway engineering, tram, tram-train, timetabling, transport planning.

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1. Introduction

Sustainable application of smart transport solutions in developed as well as developing countries remains one of the most challenging issues of today. The massive growth in car ownership over the last decades has become unbearable for the city environment. As the situation within the field of urban mobility in the dense-populated urban areas of both eastern and western European cities reached its climax, regulations, and public policy in favour of the sustainable transport modes and support of the smart urban transport solutions (Janoš, Kříž 2018) manage to decrease the modal share of private cars.

The bigger and significant European cities without proper rail-based high-capacity transport try to introduce new urban or suburban systems with routing and technical features conveniently optimized to meet the current needs and technical standards without historical constraints. The choice of the most suitable system may followingly be conducted using muti-criteria approaches (Jakimavičius, Burinskienė 2013). However, this is often not the case with middle-sized cities and their regional transport bonds. Insufficient infrastructure unsuitable for fast and expensive high-capacity suburban rapid transit directly linking the origins in the region and the destinations in the city center resolves in a substantial part of the transport demand being conducted by unattractive or unsuitable road transport modes (i.e., suburban buses and private cars). The responsible regional transport authorities may face a challenge whether to take the conventional solution or to combine the distinctive features of various rail systems to gain an efficient and comfortable transport solution at an acceptable quality level to customer satisfaction (Valášková, Križanová 2008).

One of the solutions that cover the above-mentioned weaknesses seems to be the combination of urban and suburban rail features – a tram-train, which integrates these 2 distinctive approaches into one technically challenging but operationally attractive concept with a direct connection between existing regional railways and destinations in the agglomeration center (Novales *et al.* 2002). In this article, a potential introduction of this transport system as a result of the comparative analysis of suitability between the different approaches in the Olomouc Urban Agglomeration is discussed. Special attention is paid to the proposal of both technical and operational aspects of the Olomouc tram-train system as an integral part of the regional public transportation network.

Although the tram-train solution has repeatedly been mentioned in the official regional public transport planning documents such as the regional mobility plan, it has been perceived as a mere option without specific time schedules, system implementation scenario, or even technical and technological parameters. With this article, the authors try to compensate for this absence by presenting the detailed approach featuring operational concept and technical as well as economical aspects of the tram-train system implementation. The main aim of the adopted approach is to contribute to the system's practical introduction by proposing its functional integration into the regional transport grid and further developing the ideas set by the regional transport policy.

2. Art of statement

The tram-train represents a mainly suburban means of public transport that integrates regional commuter and urban passenger demand by offering a direct (transfer-free) link from the regional areas to the center of the agglomeration (Savchuk, Nahornyi 2020) by using usually both the railway and urban tram infrastructure. An introduction of the tram-train system must be preceded by proper suitability and assessment of whether the chosen urban area fulfils the prerequisites for a successful tram-train system application defined by Naegeli *et al.* (2012). As seen in the current urban and regional networks featuring tram-train lines, although the different systems share the main operational or supply traits, the actual execution is strongly influenced by different specifics of the region (Metelka, Janoš 2021). For example, there are only full-electric units in both mixed operation with trams and trains in operation within the large Karlsruhe system whereas, in France, a tram-train vehicle is rather perceived as a simple light-rail system with limited connections to the urban network (with exceptions of Paris, Bondy, Montfermeil or Mulhouse). Some other projects in middle-sized cities were also considered, i.e., in Saint-Étienne (France) (L'Hostis *et al.* 2016). In Kassel (Germany) mixed operation with firm functional integration in a regional rail transport supply is always provided by electric or diesel-electric units providing direct connections to the Kassel city center via by adapting the disused subterranean tram stop within the main railway station (Holzapfel, Meyfahrt 2015). However, several systems are rather an expansion of the modified tramcars in the isolated railway lines without general compatibility (for example, Nordhausen (Germany)) and there are even examples of a mixed operation with a standard subway system in Zoetermeer or Hague (Netherland) with the *RandstadRail* services (Badcock 2006). Some rapid suburban tramway systems as an extension of the urban network should not be confused with regular tram-train even though they may share some technical and operational features (Richer, Hasiak 2014). The same phenomenon is to be spotted with the proposed systems where the less effective hybrid units are still present (Maternini *et al.* 2014) although fossil fuels are hardly perceived as sustainable and the tendency to replace them with ecological solutions is undeniable. Despite the railway line refurbishment, electrification and adaptations needed for the tram-train operation requiring corresponding funding, the tram-train system may represent an economically viable solution for a middle-sized city (Ventura *et al.* 2022). Nevertheless, the introduction of an attractive rapid transport service with an accessibility increase may support the housing development of the affected areas (Połom *et al.* 2018).

In the Central European countries, many middle-sized tram networks survived 2nd half of the twentieth century with the rise of individual car-based modes. As defined by Durzyński *et al.* (2018) for Poland several technical and legal adjustments must be applied to ensure the successful incorporation of the tram-train services into the existing urban tram networks (as for the Czech conditions, some of them are further listed in Chapter 5). The phenomenon of a tram-train line introduction in the technical conditions of the Czechia was discussed by Velek (2015), who, however, did not include Olomouc in his tram-train proposals. Regarding the potential for the tram-train system introduction in Olomouc and its surroundings, several authors conducted studies focusing on the suitability of such a system in Olomouc conditions with different attention to detail. For example, Potěšil & Molková (2006) found Olomouc as being suitable for a tram-train system introduction and further discussed the application with all regional railway lines heading to Olomouc main station. The authors, however, were focused on the mere replacement of the regular regional train service with a tram-train service in the busiest sections and they did not consider regional bus replacement or the mixed operation with fast or freight trains. The comparative analysis between the train and tram-train alternative after the reconstruction of the chosen line between Olomouc and Uničov was not provided so it is not clear whether the claimed travel time reductions would have been possible to reach with the trains only. Besides, the interchange elimination time gain was questioned by the preferred connection to the tram network, which adds an additional 6 min of travel time. Moreover, as the study is about 15 years old, changes in the regional transport policy have resulted in conducting the more complex line reconstruction with estimated dynamic regional railway units operating at speeds up to 160 km/h scheduled to open in 2023. This reconstruction aims at gaining more relevant travel time savings and attracting passengers from buses and individual modes. The role of the light-rail system (tram network) in the city was proclaimed very important by Kołoś & Taczanowski (2016), who presented a comparative study of the selected Central European middle-sized cities characteristics in relation to rail-based means of public transport. Another study was conducted by Pilgr (2017), but the results did not respect the principles of the regional public transport supply design with headways of 55 or 70 min and did not utilize the main advantage of the tram-train – interchange-free journey to the city center and related travel time reductions.

In conclusion, although some authors aimed to analyse the tram-train suitability for the Olomouc Region, the complex view with the newest development in both urban tram and regional railway improvements considered is yet to be made. The previous works were either less specific or did not consider the functional integration of the new tram-train system to the regional transport as well as urban tram network and their coexistence or cooperation. The already proposed concepts mainly aimed at the substitution of the current railway operation instead of replacing regional bus lines by utilizing the demand streams into the regional railway lines. Moreover, these studies are of older origin and therefore are not able to cover the newest development regarding the expansion of the tram network or ongoing upgrade of the regional railway lines. The holistic approach featuring not only the initial case study, but also the following proposal of operational concept, vehicle parameters, and related financial aspects will be 1st provided in this article.

3. Problem area description

The city of Olomouc (some 100000 inhabitants) and its surroundings including the neighbouring towns: Šternberk, Uničov, Prostějov, and Přerov – form the Olomouc Urban Agglomeration with a population of over 250000 inhabitants. The city itself is an important local as well as trans-regional center of education, research and development, employment, and administration.

The city is also an important railway node with the main station being the 3rd busiest railway station in the Czechia. In total there are 5 railway lines with different parameters: line No 270 is the only double-track line as it is part of the Trans-European Transport Network(TEN-T), it has a single-track electrified branch heading south to Prostějov and Brno, line No 290 is a regional line with growing potential after recent modernization and electrification according to railway standards. The 2 remaining single-track non-electrified regional railway lines require a systematic solution for the upcoming modernization of the regional network, and they will therefore be discussed further – the radial line No 310 and most importantly the city-crossing line No 309 complemented by the part of line No 307 that connects the town of Litovel to the network. The railway network of the Olomouc Region is displayed in Figure 1.

Figure 1. Map of the Olomouc regional railway network with the discussed lines and its stops marked bold (source: *https://www.mapy.cz*)

Moreover, the city of Olomouc boasts a functioning tram system with an overall length of up to 15 km that has been modernized and gradually extended over the last 30 years. Although the trams are quite popular with the passengers and considered being the arterial urban public transport mode, their overall transport performance is smaller than urban buses. This unsustainable result is caused by the missing tram links to the most populated residential area in the city, some of which are being built only recently. However, this state may be reversed by using the existing tramway infrastructure for the additional regional rail mode that can cover some of the urban transport needs – the tram-train.

4. Suitable approaches for suburban transport

As most of the villages and towns near Olomouc have significantly risen its population over the last 10 years, the modal split of regional trains has gone from stagnation to minor increase, the use of regional bus lines has significantly declined due to the competition of private cars. It seems that the only way how to make suburban transport more attractive to passengers is to improve the transport supply by introducing modern rapid rail transport. Apart from the rather undesirable status quo preservation, there are 2 different ways how to systematically upgrade the regional network – conventional refurbishment of the chosen railway lines with the operation of new middle-capacity electric units or reconstruction of the suitable sections in combination with the existing tram network with the operation of the light-rail tram-train vehicles. The potential conventional tramway operating in the region was rejected as it did not fulfil the initial conditions of reaching speeds up to 100 km/h that enable the operation of freight trains and semi-fast long-distance passenger trains on the lines. As these products cannot be fully withdrawn from the current railway infrastructure, the potential regional tramway line with the operation of standard tramcars would have to be built alongside the existing railway line. Thus, this approach generates both construction difficulties and operational inefficiency.

4.1. Status quo with minor improvements

As mentioned before, the current infrastructure and operational state of the primarily discussed railway lines No 307, 309, and 310 allow hardly any comparative advantages for the railway mode and restricts its competitiveness. Line No 310 shows signs of negative stability, as there is a minor decline in passenger numbers despite the villages along the line growing in population. Apart from the low maximum speed on the line, the main reason may be both physically and morally outdated uncomfortable diesel units used today. It is not probable to keep the passenger numbers of today in the next years unless a big investment regarding both vehicles and infrastructure to make the railway more attractive is made.

A similar situation may be spotted with line No 309, which has grown its passenger potential by 25% in the last 5 years by tariff and operational means only. However, no further growth is expected with the current maximum speed of 60 km/h and negligible distance of its stations in Olomouc from the city center resulting in travel times extension caused by the need of using public transport for the last mile. However, its possibilities for multimodal passenger travel (Smoliner *et al.* 2018) as well as for a limited amount of freight transport should be emphasized.

The status quo is unsustainable in every aspect as it causes a considerable rise in the external environmental costs, time losses and discourages the passengers from using regional public transport on a regular basis. This phenomenon cannot be outweighed by smaller operational costs as every further concept change in favour of the system attractivity needs high investments anyway.

4.2. Modernization of the lines and operation of conventional vehicles

As the reconstruction, electrification, and optimization of the railway lines listed above are needed anyway, the 1st logical solution coming to one's mind might be the use of conventional electric railway units for regional railways. Its advantages are widely used and proven technologies, lower prices since such units are produced in massive series, producer competition, and universal use in either part of the national railway system with the same propulsion system. With the refurbishment of the railway lines being done, no additional legislative complications are to be awaited.

However, significant disadvantages are to be spotted by the conventional solution as far as the relationship between costs and revenues is concerned. The dynamics of regional electric railway units may be satisfactory enough but within the city borders with the densely arranged stops, the heavy vehicles usually struggle to reach the maximum allowed travel speed (although this value is expected to reach only 60 km/h within the city borders) as they must break again for the next stop. A feature that restricts the creation of additional stops in the city limits its potential as an effective and attractive replacement of the urban buses (as a link between the city center and the city outskirts) as well as the suburban buses (as a link between Olomouc, Litovel and the villages between them). Furthermore, the travel times difference on the new infrastructure does not eliminate the main problem with the all 3 relations (Drahanovice, Litovel, and Hrubá Voda) – the need for a change with the public transport since the railway stations (Olomouc Město, Olomouc-Nová Ulice, Olomouc main station) are not less than 500 m from the destination area, the city center. Even the refurbished infrastructure and modern trains cannot outweigh the persisting need to change for additional urban trams and buses and cannot prevent the passengers from the related travel time increase. In addition, utilizing the whole line No 309 restricts the regular cargo trains heading to the Olomouc heating plant and other freight trains operated on this line.

Despite its unavoidable investment costs, this model can by no means replace the existing urban and suburban bus lines as it serves as an isolated connection to the Olomouc main railway station without offering a direct connection to the destination point – the city center. That can be by no means labelled as a satisfactory solution when the amount of invested money is considered.

4.3. Tram-train

Most of the problems mentioned in the previous section can be solved by introducing a tram-train system. Its main advantage lies in the fact it can combine the positive features of the train and a tram and utilize them whenever it is needed. The tram-train system enables direct connections from the outer region to the city center, integration with both tram lines and long-distance trains (zone-oriented timetable on line No 310), travel times that correspond to the express buses with the level of service offered only by local buses. Thus, all the buses between Olomouc and Litovel can be replaced by the tram-train creating a significant improvement of the middle-sized regional transport system effectivity as a desirable feature of the tram-train introduction (Kołoś, Taczanowski 2016). The light-rail vehicles and their dynamics pose no problem to the eventuality of creating new stops within the city of Olomouc and the high frequency of the tram-train represents a tram-like alternative for the people living in the boroughs of Olomouc. This phenomenon brings the passengers both frequent and comfortable urban tram and rapid suburban railway in one vehicle.

The tram-train network proposal combines the existing parts of the railway lines No 307, 309, and 310 with the new tram tunnel, existing urban tramway infrastructure, and relocations of the current railway infrastructure in favour of service availability increase. Not the whole line has to be upgraded, which can significantly positively influence the overall budget. Moreover, the space for freight trains to the heating plant is provided on the abandoned part of the line in the city with the possibility to manipulate there almost any time of day. The freight transport during the off-peak hours is also possible on the original railway lines after the refurbishment.

The main obstacles one must deal with when introducing a new tram-train system in the conditions of the Czechia are the lack of experience with such vehicles and, more importantly, the lack of appropriate legislation. The lack of legislation is a common problem for all the Central European countries where an introduction of the tram-train is proposed. Apart from the Czechia, similar questions have been posed in Poland (Makuch 2017; Adamkiewicz 2020). However, as it was experienced in Karlsruhe (Germany) the process from the 1st idea to the 1st ride may last no more than 10 years of thorough planning and construction works and it is not as improbable as it may have seen at the very beginning. It is also expected for the complicated tram-train vehicles to be even more expensive than the regional railway units.

4.4. Comparison

For the detailed and conclusive summary of the distinctive features of both alternatives see Table. As far as infrastructure costs are concerned, the table includes only the comparison of refurbishment and new section costs regarding the railway lines No 307 and 309. The modernization of the line No 310 is not included in the comparison since its parameters are the same for both alternatives and the renovation is unavoidable. The tramway tunnel under the main railway station with estimated costs of 58.14 mln. € is also not included, because it is a shared investment between the city and regional government and this model decreases the overall costs for the regional government. Moreover, although the network is complete and utilizes a maximum of its potential only with the tunnel in operation, the launching of the tram-train lines is not dependent on its opening (see the appropriate section in Chapter 5).

As it is seen from the table, the operational benefits are by far better by the tram-train alternative. From the financial point of view, it is to be demonstrated that the 4 km section in Olomouc where the already existing and perfectly suitable tramway infrastructure is used to transport the passengers directly to their destination point resulting in significant door-to-door travel time reductions that represent the main benefits of the tram-train alternative. The necessary tram network adjustments that enable tram-train operation (i.e., rail arrangement or switch changes) are expected to be provided in terms of standard track maintenance and thus do not generate additional costs. Moreover, savings are to be gained by replacing the existing urban and suburban bus lines as there will be lower personnel requirements.

The main threat that is associated with the tram-train alternative in the Olomouc Region is the missing legislation and Czech Technical Standards for the tram-train vehicles and the related slightly higher price per one tram-train unit. The necessity of new unstandardized technical solutions regarding the vehicles in the countries with missing tram-train legislation has recently been shown in Hungary (Bocz, Vinkó 2017). The estimated higher operational costs in comparison with standard trains may be somewhat compensated by the already discussed full substitution of the frequently operated regional and urban bus lines. The lack of funding, which usually prevents similar regional projects from being implemented or reduces their extent, is similar for both tram-train and conventional railway alternative and eventually leads to an undesirable status quo preservation scenario.

Although the presented analysis and comparison focus only on the proposed systems in the Olomouc Region, some basic guidelines for choosing the suitable railway lines for the tram-train system introduction may be spotted. The fast arterial railways (line No 270 in this case) may not utilize the maximum potential of the tram-train as they usually provide a fast approach to the city, which compensates for the somewhat longer transfer time. However, under some circumstances (i.e., sufficient residual capacity for the tram-train vehicles and potential for the diversion of the tram-train through the city in a tram mode and return to the mainline) the tram-train may complement the fast train supply, which is not the case for Olomouc. In addition, the lines that are sufficiently served by modern regional railway vehicles with the corresponding higher stopping distances and frequent regional rapid transit service are not very suitable for the tram-train introduction (e.g., line No 301).

In contrast to the above-mentioned unsuitable infrastructure types, the following 2 main concepts integrate the tram-train well into the regional public transport grid – the poorly used slow regional railway lines and the slower lines with zone-oriented timetable possibility and medium passenger flows. The 1st can offer the already existing infrastructure to be refurbished, modified solely according to the tram-train operation or infrastructure needs, and connected to the urban tram network. This is represented by the chosen line No 309. There must be the freight trains operation requirement at least at night, otherwise, it would be better to introduce a more conventional suburban tram operation as a full substitution of the current railway lines.

Table. Comparison of the conventional train and tram-train alternative

Aspect	Conventional train	Tram-train
Dynamics in slower speeds	medium	high
Legislation	complete	missing
Replacement of urban buses	no	yes
replacement of suburban buses	no	yes
direct connection to the center	no	yes
New or modernized single-track length [km]	40.16	33.43
Units required (all stages)	10	10
Estimated costs per unit [mln. €]	5.06	5.26

In addition, the line features densely populated line-shaped suburbs along the north section of the current railway line located in a valley making it the only feasible radial public transport infrastructure option. The zonal concept reduces the investment necessary for the operation as only the inner zone with the mixed operation of conventional semi-fast trains and the tram-train requires refurbishment (line No 310). The semi-fast trains have a limited amount of stops in the inner zone and may end at the railway station whereas the tram-train stops more frequently and continues to the city center via tram network.

5. Operational concept

5.1. Operation

The operational concept uses the following technical, technological, and operational features. It was designed as an attractive alternative to both regional bus service and private cars. It uses the principles of periodic timetable with its international conventions (the basic time of symmetry corresponds approximately to the min 0). It defines the periodic timetable nodes that are transformed into multimodal interchange terminals. At the same time, it respects the restrictive conditions of the Olomouc tram network and the limits of the modernized infrastructure. The feasibility of the proposed solutions concerning travel times and the cooperation vehicle, infrastructure was verified using a special timetable construction software *Fahrplanbearbeitungssystem* (FBS, *https://www.irfp.de/das-fahrplanbearbeitungssystem-fbs.html*).

5.1.1. General

For both proposed lines, the minimum headway of 30 min at the peak hours and 60 min off-peak is expected. That forms a common 15/30 min headway on the trunk route, which makes the tram-train line a perfect alternative for the urban buses and a more comfortable, ecologic, and faster alternative of suburban regional buses.

The operation ranges from about 4.15 a.m. (as there is a necessity for the 1st connection to reach the Olomouc city center before 6 a.m.) to 0.15 a.m. the following day (since the last connection heading to the region is expected to depart after 11 p.m. from the Olomouc city center). At the weekend, the end of the operation is extended by 1 h. The infrastructure and operational concept enable the transport authority to add another semi-fast connection during the morning peak hours in order of higher transport demand from Litovel.

5.1.2. Tram-train lines

For the whole network, 2 lines are proposed:

- TT1: Olomouc-Bělidla (tram section) – Olomouc main station – Olomouc-Náměstí Hrdinů – Olomouc-Hejčín (railway section) – Příkazy – Náměšť na Hané – Drahanovice central;
- TT2: Hrubá Voda – Velká Bystřice – Olomouc main station (tram section) – Olomouc Náměstí Hrdinů – Olomouc-Hejčín (railway section) – Příkazy – Unčovice Village (tram section) – Litovel-Město (railway section) – Červenka.

The main origins and destinations are appointed to be the periodic timetable nodes and they, therefore, enable simple and reliable interchange to bus lines serving the nearest area. That is the case with Hlubočky-Mariánské Údolí with an important machinery production (node 30´), the station Litovel-město located in the center of Litovel with nearly 10000 inhabitants (node 30´), Drahanovice with bus connections further west (node 15´/45´ during peak hours) or the village of Příkazy (node 15´/45´). Detailed information about the timetable is provided in a form of the *NetGraph* (Michl *et al.* 2017) displayed in Figure 2.

5.1.3. Alternative for building in stages

As shown in Table, infrastructure refurbishment costs represent a substantial part of the total project costs. Since the regional governments usually cannot invest vast sums in a limited period, the proposal enables the public authorities to relocate the money for the project by step-by-step construction.

There are 3 main stages of the project:

- the 1st stage IA, consisting of line TT1 Olomouc main station – Drahanovice central only enables the provider to gain the necessary operational experience and the transport authority to test its suitability for the region with minimum additional infrastructure costs. The only important investment is the refurbishment of most of the railway line No 309 and its connection to the tram network. The simplicity is negatively outweighed by its small benefits in comparison with the following stages;
- the 2nd stage IB adds the 2nd line TT2 between Olomouc main station and Červenka connecting the important town of Litovel and its neighboring villages along the line. This stage brings a complete elimination of regional bus service between Olomouc and Litovel and a significant reduction of urban buses. Together with the stage IA, both tram-train lines end near the building of the Olomouc main station in the public transport terminal;
- the most expensive part of the proposal (3rd stage) is the tram tunnel, which forms the condition of connecting

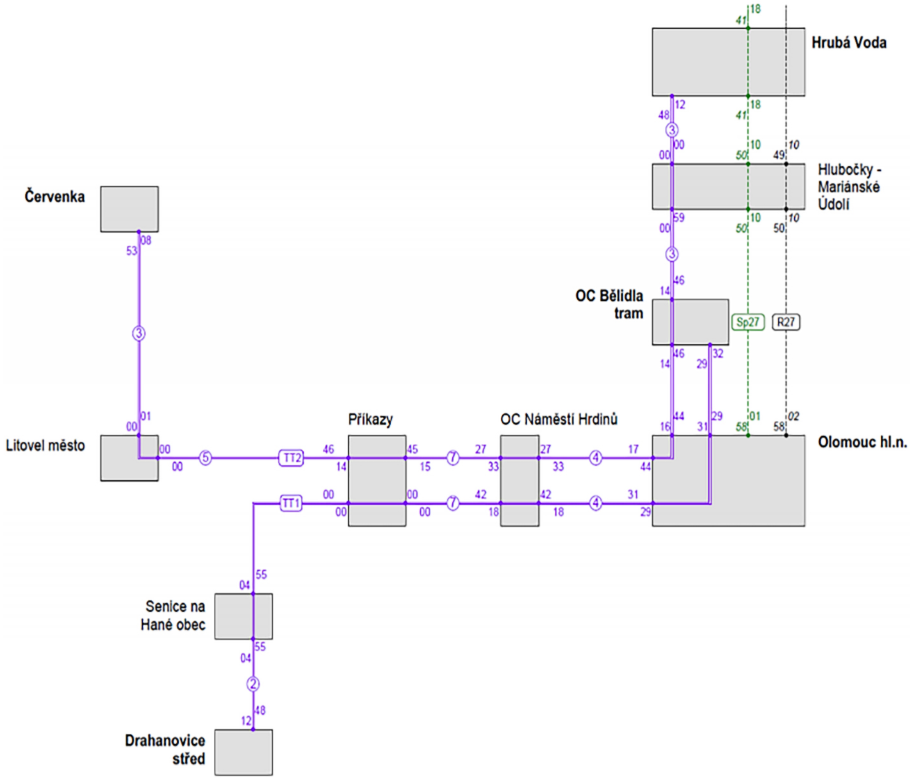

Figure 2. *NetGraph* of the maximum proposed tram-train network together with the semi-fast and long-distance trains on line No 310 (source: compiled by authors)

the line No 310 and extension of the line TT2 to Hrubá Voda and the line TT1 to Bělidla. Only with this stage completed the whole system can utilize all its benefits to both urban and suburban transport demand. It is therefore recommended to build all 3 stages subsequently.

5.2. Infrastructure

As stated before, the tram-train system is proposed to utilize the advantages of both subsystems and to choose the appropriate system according to the local suitability. The flexible change between tram and railway operation remains one of the most distinctive features of the tram-train system and should, therefore, be taken advantage of.

5.2.1. Tramway and railway lines

All 3 of the used existing railway lines (No 307, 309, and 310) will be refurbished with special attention paid to meeting the standards of modern and successful suburban light rapid transit. According to the local geographical possibilities, the maximum speed will be raised to 100 km/h. If such considerable speed rise cannot be achieved by the simple reconstruction alone or if the existing stations are too far from the built-up area of the villages, the local relocations of the line are proposed. The total length of the newly relocated parts is 4.625 km.

Since the railway line No 307 in its section between the stations Senice na Hané and Litovel předměstí is not suitable for the proposed concept due to its excessive length, slow speeds, and unacceptable distance of its stations from the rather less populated areas along the line, it is suggested for closure. As an effective and more direct replacement a new line along the highway D35 with direct and frequent service for all the growing villages between Příkazy and Litovel (Náklo, Unčovice, and Rozvadovice) and the town of Litovel itself. Because of the limited space by the highway exit near Unčovice, 2 alternatives were evaluated. The 1st one comprises a new railway line between Unčovice and Litovel, the 2nd one takes advantage of the sharper curve and goes right through the village and with further stops in Rozvadovice and 2 times on the outskirts of Litovel. As there is the need to place the line in the relatively narrow streets, the entire section is here proposed as a suburban tram line with a maximum speed of 80 km/h. Both alternatives are displayed in Figure 3.

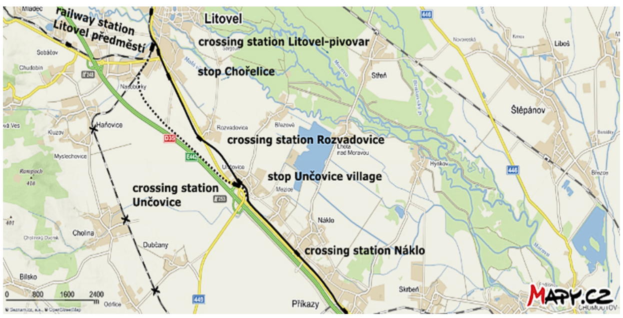

Figure 3. A map of the 2 alternative solutions of the newly-built section Unčovice – Litovel, the chosen tram alternative marked bold, the railway alternative is dotted (source: *https://www.mapy.cz*)

Both alternatives were evaluated using the timetable construction software FBS. Although the railway alternative seemed to be faster, the difference was only 3 min, and it did not cover the important villages and therefore did not allow the complete replacement of the bus lines. Thus, the tram alternative with further connecting to the railway line to the north of the current railway station of line 309 was chosen. The total length of the new line between Příkazy and Litovel is 9.037 km with the tram section representing 4.79 km.

To reduce the construction costs and space requirements of the system, the current single-track railway lines are left single-track. Some exceptions may be spotted with the section between Horka nad Moravou and Olomouc-Řepčín because of the operational concept requirements. With the basic timetable guidelines and the set headways mentioned before, the crossing of the trains comes out directly in the middle of the section. However, due to the lack of space between the road and the only recently built cycle path, this section is built as double-track only for the tram-train vehicles. Because of a smaller distance between the 2 tracks, it is considered being single-track for standard freight trains.

5.2.2. Power supply system

Both regional railway lines with the proposed tram-train operation have not been electrified so far. Although the prevailing power system according to the overall transport performance in the Czechia is 3 kV DC, a conversion in favour of the system 25 kV AC, 50 Hz is expected. Every railway section of the tram-train line is therefore electrified by 25 kV AC, 50 Hz. If it is not feasible to apply such high voltage (urban areas with close distances to private objects and track sections with the future possibility of mixed operation with urban trams) the tram power supply system 600 V DC is used. This setup enables maximum synergic utilization of the current railway infrastructure and the vehicle parameters described before. With the higher frequency of service, the higher initial infrastructure expenditures are compensated by less complex dynamic full electric vehicles with lower total costs of operation.

5.2.3 Stations and level crossings

The configuration of the railway stations depends heavily on their transport significance for both long-distance passenger and more importantly freight transport. If the original station offers both good position according to the local transport demand and access or waiting point for the freight trains, it is preserved in its original railway-based configuration (e.g., Hlubočky-Mariánské Údolí). If the current position of the station is not attractive enough for the passengers, it is left for the use of freight transport only or eventually relocated in favour of a shorter approach from the villages (Senice na Hané).

The rest of the stations are reduced to the minimum size, which lowers the maintenance and operation costs. There are special stations for the regular and occasional crossing of the trains that are suitable for the length equivalent of one vehicle only. These stations are built whenever it is possible and acceptable when additional costs for the land are considered. Apart from the regularly used ones, their locations respond to the standard deviations initiated in the urban tram network as they can eliminate the delay transition on a single-track line (Ricci *et al.* 2017). The rest of these stations enable adding supplementary trains during peak hours in case of higher demand and increase the overall stability and flexibility of the system without a significant rise in its costs.

5.2.4. Platform height and shape

One of the greatest compatibility challenges of the tram-train systems using existing tramway infrastructure is to determine the optimal platform height above the track level. The Olomouc tram network currently uses the heights 160...200 mm above the track level whereas the usual entrance height of the Olomouc low-floor tramcars is 350...360 mm, which leaves some 150 mm of unacceptable and uncomfortable height difference the passengers must overcome. The proposed solution with low-floor tram-train vehicles utilize their height similarities to the already operated urban tramcars and sets the height of the shared stops within the city borders to 300 mm above the track level, which seems to cover the existing vertical differences caused by different wear and tear of the tram wheels satisfactorily. In addition, the chosen height corresponds to the phenomenon of increasing the accessibility of the urban transport by long-term infrastructure means instead of unreliable vehicle features such as ramps and at the same time, it reduces the overall boarding time.

However, the railway platform height according to Czech Standards is 550 mm above the track level (Matuška 2017). If there is a mixed service with conventional railway vehicles and some of the platforms must be shared with both service layers, 2-section platforms with different heights (550 and 350 mm) are recommended. If the station itself is expected to serve as a terminus of the tram-train line (e.g., Hrubá Voda station), the lower tram-train platforms are supposed to be separated from the higher train platform.

Apart from the vertical difference, a horizontal difference should also be mentioned since the mixed operation of the passenger as well as a freight train with wider outlines than the tram-train vehicles (Maternini *et al.* 2014) is planned and required. This difference may be simply overcome by horizontal movable platform active only with the railway-compatible platforms as it is used in the city of Kassel and surrounding railway lines.

5.2.5. Tram tunnel

To make the most of the tram-train system advantages such as the fast and direct connection from the region to the city center (especially for the non-existent connection from the area of the railway line No 310), a creation of a capacity link that bypasses the existing tram route is required. The proposed cut and cover tram tunnel under the main railway station with its length of approximately 460 m (Metelka 2019) includes one underground station directly under the main railway station. Using direct exits to the main platforms of the railway station, this solution minimizes the transfer time from the city and region to the long-distance trains and conventional regional rail services. Moreover, this tunnel will be used by the tram lines linking the eastern suburbs of the city, which either cannot be linked directly to the main railway station due to street configuration or cannot utilize the competitive travel time.

Although the tunnel discussed above may be the most expensive part of the new infrastructure, it enables the whole tram-train system to use all its advantages. Moreover, the project of the tunnel for the urban trams only is already a part of the strategic documents of the city. The simultaneous operation allows the total costs to be distributed between the city and the region with both authorities saving money if they were to pay the highly needed tunnel alone.

5.3. Vehicles

Tram-train vehicles are usually produced in small series with a higher level of adjustment to the specific conditions and requirements of each tram-train system. If there is a brand-new system to be created today (as in the case of the proposed network in the Olomouc Region) it can make the most of the already functioning solutions used in the last 30 years of the tram-train development, pick the most suitable ones and combine them to fulfil restrictive conditions defined mainly by the Olomouc tram network and Czech operation and legislation procedures.

5.3.1. Dimensions and capacity

There are several types of vehicles that differ from each other according to their key parameters. With the exclusion of middle-floor and high-floor vehicles that do not seem to meet the current accessibility standards despite their preservation in the current railway operation in Olomouc Region (Matuška 2017), there are 3 main length categories:

- approximately 52 m long 12-axle 5-segment vehicle with over 150 seating places;
- approximately 42 m long 10-axle 4-segment vehicle with over 90 seating places;
- approximately 37 m long 8-axle 3- or 5-segment vehicle with up to 90 seating places.

The maximum length of the current multiple units in the tram fleet of Olomouc is about 30 m and the tram stops are adjusted to that length or its multiples, it is, therefore, desirable to exceed this value only by the smallest acceptable vehicle length. With the current rail vehicle seating capacities and the above-described operation frequency considered, the 37 m long vehicle is chosen as the most suitable for this operational concept.

As far as width is concerned, the producers offer tram-train vehicles ranging from 2.40 to 2.65 m. The tramcars operated in the Olomouc tram network have a maximum width of 2.50 m. For the new tram-train units, it is recommended that the network should be analysed if there are any curves or high platforms that collide with the vehicle width up to 2.55 m, and according to that, the proper vehicle width should be chosen. It comes as a matter of fact that the maximum suitable width should be applied as it improves spatial comfort and makes the middle aisle more passable.

5.3.2. Configuration

Concerning the already introduced solutions, 2 main vehicle configurations within the chosen length restrictions are to be spotted: urban and suburban. The urban configuration with more doors and related space for standing passengers is suitable when the tram section within the core city borders is long enough and very heavy passenger changes are expected. On the other hand, most of the seats are placed face-to-face usually in groups of 4 so the typical longer journey in the region with a higher load factor spotted usually during the peak hours results in uncomfortable seating and even in the presence of standing passengers. Both short and long-distance passengers share each vehicle section, which causes interference between these 2 groups. Both 3-segment and 5-segment vehicles with this configuration are commonly operated in Europe.

The suburban configuration, however, expects the tram section in the city to be significantly shorter than the rest of the route in the region and that enables the interior of the vehicle to be divided into 2 (3) different compartments that usually do not cause the different travel groups to interfere with one another as each group chooses their particular vehicle section. The common practice (as there is only a 3-segment vehicle available for this configuration) is to allocate the middle section of the vehicle with no doors for long-distance travellers. There are seats with the 2+2 and row configuration, which increases the offered seating capacity. The remaining front and rear sections serve the short distance urban travellers who can bear to stand in the urban section or chooses the additional seats on the front bogie pair. As this configuration enables the separation of the short and long-distance travellers and tries to avoid unacceptable standing with longer journeys, it was chosen as the most suitable for the Olomouc tram-train system.

5.3.3. Propulsion

The Olomouc tram network uses a conventional power supply via 600 V DC overhead wires. The main railway corridor and one other long-distance railway line are electrified with 3 kV DC but the remaining railway lines (including the ones with the proposed tram-train operation) are not electrified. As there is a long-term plan to unite the railway power system in favour of higher voltages (25 kV, 50 Hz AC) due to its higher efficiency (Seelmann 2014), it can be successfully expected such conversion of the

Olomouc railway node to be completed by the time of the tram-train operation launches. As the diesel engines are neither ecological nor dynamic and economical in the long-term view, dual-voltage operation of the tram-train vehicles with 600 V DC for the tram sections (city of Olomouc, Unčovice, and Litovel area) and 25 kV, 50 Hz AC for the railway sections is recommended.

Although some systems based on diesel-electric hybrid units have recently been launched (e.g., Szeged), this option was not further developed. The main issues comprise worse dynamics of such units in the diesel mode, even more complex and expensive units with higher operational costs, inability to utilize the existing and planned railway power substations (network synergy) and problematic aspects regarding the sustainability policy adopted by the Czechia (e.g., Paris Agreement or Green Deal). As for the battery-electric units, the operational concept does not guarantee dynamic recharging as there is not enough voltage in the tram network and power for the charging station would have to be brought to the regional termini the same way as with the full electrification scenario. Moreover, the battery-electric units feature higher purchase and battery maintenance costs (Borghetti *et al.* 2021). Similar restrictions together with financial inefficiency were identified with the hydrogen vehicles that are not able to utilize the existing tramway infrastructure for its propulsion and integration of a fuel cell technology into the dual-powered vehicles increases their complexity and related purchase as well as operational costs.

5.3.4. Purchase and maintenance

Since the potential of forming complex and interconnected transport networks is somewhat limited for the usually complementary tram-train systems, the vehicles are produced in small series with different features resulting in higher purchase costs per vehicle and smaller motivation of the manufacturers to participate in such tenders. It is therefore recommended to conduct one big tender for all the required vehicles with partial deliveries according to the actual vehicle needs for each project stage. To make the tender more attractive and to reduce the maintenance costs over the years of operation, the maintenance model Full Service provided by the manufacturer is proposed.

As the vehicles are owned by the regional government, a special tender for the carrier is expected. This model enables both private and government- or state-owned railway carrier to participate without further restrictions and obstacles that may discourage potential new carriers.

There are 3 different companies responsible for track maintenance. The maintenance of the railway line No 310 remains under the Czech national infrastructure manager "Správa železnic" since there is a mixed operation not only with freight trains during the day but also with faster long-distance passenger trains. A different approach is chosen with the railway lines No 307 and 309 including their new sections. The operation of freight trains is planned only during night hours so there is no need to leave the control over these lines to the national infrastructure manager. It is therefore recommended to establish a new company with its majority being owned by the municipality and to maintain the lines independently. Finally, all the tram sections within the Olomouc city borders are expected to be maintained by DPMO (in Czech: *Dopravní podnik města Olomouce*, *https://www.dpmo.cz*), the Olomouc public transport operator that already provides maintenance for the Olomouc tram lines.

6. Conclusions

When applied right in the suitable urban agglomeration with the developed tram network in the core city and a perspective regional railway lines with the limited residual potential of offering sufficient passengers' benefits regarding the currently supplied travel times and frequency (Naegeli *et al.* 2012), the tram-train systems has proven to be a successful part of the regional rapid transit scheme and may even encourage the development of near its access points (Richer, Hasiak 2014). If there is a possibility to reduce travel times by elimination of the interchanges without undesirable loss of comfort provided by conventional regional railway vehicles a tram-train may seem as technically, technologically, and operationally sane alternative.

Such prerequisites have been successfully met in the Olomouc Region. For the costs equivalent to the necessary complete refurbishment of the slow and insufficient regional railway lines, much more can be achieved with the tram-train. Regardless if it serves as an effective new tram line for the new boroughs of the city, a rapid light-rail connection from the regional origins to the destination in the city, an ecological and more attractive replacement of the regional bus lines or the slower and shorter complement of the semi-rapid long-distance railway lines – its versatility has the potential to fill in the blank spot in the Olomouc regional public transport supply and to reverse the unfavourable phenomenon of growing regional and suburban individual transport in such an agglomeration. These qualities have already been acknowledged by the regional authority as the possibility of tram-train operation and the proposed operational concept on the described railway lines has been incorporated in the regional transport development plan (KIDSOK 2019).

This article proposes a new feasible long-term regional transport solution for the Olomouc Region by introducing a tram-train system as an integral part of the current urban and suburban transport network. For its successful implementation, the vehicle and infrastructure parameters based on current experience and regional specifics were defined. Eventually, the new original tram-train operational concept represented by *NetGraph* was presented. With its preferred utilization of existing or upgraded infrastructure and its harmonic integration into the regional transport grid, it may serve as an example of how to face the challenges of prevailing individual regional transport modes in the middle-sized agglomerations with limited capacity and financial requirements. For acceptable costs, the system accommodates the new suburban residents and provides them with attractive direct connection to the city center in similar quality as in the city itself, which may eventually lead to a higher load factor of the system and an important sustainable mobility increase. Such effects are desirable since the trend of suburbanization is connected to higher use of individual transport modes and the related overuse of rural road infrastructure not adjusted to new requirements.

The results of this case study may contribute to the decision of whether such systems are to be introduced in similar agglomerations and support the local public transport planning process. However, adopting a positive decision regarding the tram-train solutions is only a 1st step for its introduction as legislation or detailed technical and operational standards like in the countries with functioning tram-train systems must be further discussed. Their modification and the best practice approach should be a subject of further research and negotiation within the responsible transport authorities and regional councils.

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Author contributions

Both authors were responsible for conceptualization, validation, investigation, and resources review.

Stanislav Metelka applied the methodology, prepared the original article draft, curated the data, and conducted the formal analysis.

Vít Janoš ensured review and editing of the article and supervised the whole process.

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