PREREQUISITES OF THE SUCCESSFUL TRAM-TRAIN SYSTEM AS A PART OF THE REGIONAL RAILWAY NETWORK

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Abstract

The idea of connecting the two of the closest urban and suburban rail-based public transport systems was proposed more than 40 years ago and it boasts a proclaimed support from the regional authorities. However, many of the systems either did not achieve their goals or became financially inefficient as they replaced the conventional railway systems in a wider range than it had initially been planned. That resulted in an inappropriate competition between the public transportation modes. This paper aims to define the prerequisites needed for the establishment of a successful, both financially and operationally sane tram-train system as a substantial part of the regional railway network An analysis of the various current tram-train systems in the selected European cities is made and special attention is paid to their distinctive features including the offered capacity, density, technical compatibility, and operational aspects. Using the conclusions of the analysis and the current technical and operational requirements to be met, a recommendation for the design and organization of the planned tram-train lines and networks is stated, which may help the transport planners design such costly systems in a way it can use its overall advantages in favor of the passengers and an increase of the public transportation modal share.

Keywords: tram-train, suburban transport systems, regional railways, interoperability, urban tram systems, mixed operation

1 Introduction

The predecessors of the current tram-train systems have been present to urban and suburban public transport networks since their creation in the second half of the nineteenth century. As there often existed a rivalry between the railway company and the urban rail transport operator, there were separate rail-based links between the main point of interest within the agglomerations. At the same time, additional private railway companies built their cheaper local railways to connect the populated areas that could not be properly served by the mainlines and to accommodate the goods flows in the regional relations. Some of the previously mentioned tramlines survived and kept its railway-like character and sometimes their historical railway legislative status concerning their urban or suburban character (e. g. the relation Mannheim – Heidelberg in Germany or Most – Litvínov in the Czech Republic). On the contrary, the local railways suffered from their inability to face the new supply chain requirements and became slow and unattractive for both passenger and freight transport.

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Some of the perspective ones were adjusted to meet the local tram standards and accommodated light rail tram-based vehicles with the operation connected to the urban tramway system (e. g. the so-called Albtalbahn in Karlsruhe, Germany).
Although these systems might share some features with the tram-train systems, none of them can be called a proper tram-train. However, its successful operation supported the idea of connecting both rail systems with mixed operation and combining the advantages of the two different systems in one product. After a decade of planning and creating suitable legislation and financing models, the first proper tram-train vehicles emerged on the refurbished regional line between Karlsruhe and Bretten in 1992. Since then, numerous applications of the system mostly in Europe were opened and each of them differs and adds specific regional features and technical solutions [1]. Concerning the evolution of the relevant legislation, all the approaches are to be analyzed to define the cities suitable for tram-train systems introduction and its optimal technical parameters.

2 Prerequisites for the tram-train system implementation

All the statements made in this chapter as well as the following ones are based on the analysis of the selected important tram-train systems in Europe opened since 1992. As not only the different networks but also the single lines within one network are quite distinctive, the overview of the analysis results available in Table 1 and Table 2 distinguish even between the different lines within one tram-train system.

2.1 Urban and settlement structure

The cities listed in Table 1 are mostly middle-sized cities with a population between 100,000 and 350,000. However, several exceptions may call a conclusion of a middle-sized city as a tram-train system prerequisite into question. The Hague has over 500,000 inhabitants but the tram-train serves as a mere urban tram line in the city and then connects the city of Zoetermeer with almost 125,000 inhabitants. The cities in the Paris conurbation form a polycentric grid so the overall area of operation may be considered one functioning middle-sized city. Thus, two of the main urban structure models of middle-sized city and its urban agglomeration may be followed as a prerequisite – the compact regional center with mainly radial or diametric journeys and a polycentric grid with the line linking several populated places and switching from the railway to tram mode whenever it is desirable and suitable.

Table 1 Overview of operational characteristics of the chosen tram-train lines

Line	Route	Travel time [min]	Peak hour frequency [min]	Tram section	Mixed operation tram	Mixed operation trains
S41	Heilbronn – Mosbach	58	60	Yes	No	Yes
S42	Heilbronn – Sinsheim	65	30	Yes	No	Yes
C13	Chemnitz Technopark – Chemnitz Hbf – Burgstädt	38	60	Yes	Yes	Yes
C14	Chemnitz Technopark – Chemnitz Hbf – Mitweida	40	60	Yes	Yes	Yes
C15	Chemnitz Technopark – Chemnitz Hbf – Hainichen	52	60	Yes	Yes	Yes
S31	Karslruhe Hbf – Odenheim	45	20	No	No	Yes
S32	Karlsruhe Hbf – Menzingen	48	20	No	No	Yes
S4	Karlsruhe – Heilbronn – Öhringen	170	15–30	Yes	Yes	Yes
S5	Wörth (Rhein) – Karlsruhe downtown – Pforzheim	90	10/20/30	Yes	Yes	Yes
S51	Germersheim – Karlsruhe downtown (– Pforzheim)	73/118	60	Yes	Yes	Yes
S52	Germersheim– Karlsruhe Hbf – Karlsruhe Tullastraße	51	60	Yes	Yes	Yes
S6	Pforzheim – Bad Wildbad	35	30	Yes	No	Yes
S7	Karlsruhe – Durmersheim – Achern	67	30–60	Yes	Yes	Yes
S71	Karlsruhe Hbf – Malsch – Achern	50	60	No	No	Yes
S8	Karlsruhe – Durmersheim – Freudenstadt – Bondorf	168	60	Yes	Yes	Yes
S81	Karlsruhe Hbf – Malsch – Freudenstadt	87	30	No	No	Yes
RT1	Kassel city – Hofgeismar-Hümme	64	30	Yes	Yes	Yes
RT4	Kassel city – Wolfhagen	69	30/60	Yes	Yes	Yes
RT5	Kassel city – Melsungen	46	30	Yes	Yes	Yes
-	Lyon St. Paul – Saint-Bel	42	30	No	No	Cargo
-	Lyon St. Paul – Brignais	25	30	No	No	Cargo
TT	Mulhouse station – Mulhouse downtown – Thann St. Jacques	44	30	Yes	Yes	Yes
T1	Nantes – Chateubriant	67	30/60	Yes	No	No
T2	Nantes – Clisson	29	30	No	No	Yes
T11	Épinay-sur-Seine – Le Bourget	15	5	No	No	Possible
T4	Aulnay-sous-Bois – Bondy, Gargan – Montfermeil	21/27	6/12	Yes	No	No*
3	The Hague city – The Hague downtown – Zoetermeer downtown	67	10	Yes	Yes	Subway
4	The Hague city – The Hague downtown – Lansingerland-Zoetermeer	58	10	Yes	Yes	Subway
S1	Lebach-Jabach – Saarbrücken downtown – Saregueminnes	71/40	7.5/15/30	Yes	No	Yes

* the infrastructure of the line remained at the railway standards, but the actual operation is conducted according to the tram standards as far as signals and crossings are concerned

Table 2 Overview of technical characteristics of the chosen tram-train lines

Line	Propulsion	Platforms	Vehicle category	Railway line type
S41	750 V DC / 15 kV, 16.7 Hz AC	high	3-section, 37–37.6 m long, high and middle floor	mainline
S42	750 V DC / 15 kV, 16.7 Hz AC	high	3-section, 37–37.6 m long, high and middle floor	mainline
C13	600 V DC / diesel	low	3-section, 37 m long	middle-frequented regional line
C14	600 V DC / diesel	low*	3-section, 37 m long	mainline
C15	600 V DC / diesel	low*	3-section, 37 m long	mainline, low-frequented regional line
S31	15 kV, 16.7 Hz AC	high	3-section, 37–37.6 m long, high and middle floor	mainline, low-frequented regional line
S32	15 kV, 16.7 Hz AC	high	3-section, 37–37.6 m long, high and middle floor	mainline, low-frequented regional line
S4	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	middle-frequented regional line
S5	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline
S51	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline
S52	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline
S6	750 V DC / 15 kV, 16.7 Hz AC	high	3-section, 37–37.6 m long, high and middle floor	low-frequented regional line
S7	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline
S71	15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline
S8	750 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline, middle-frequented regional line, low-frequented regional line
S81	15 kV, 16.7 Hz AC	high/low	3-section, 37–37.6 m long, high and middle floor	mainline, middle-frequented regional line, low-frequented regional line
RT1	600 V DC / 15 kV, 16.7 Hz AC	low	3-section, 36.8 m long	mainline
RT4	600 V DC / diesel	low	3-section, 36.8 m long	middle-frequented regional line
RT5	600 V DC / 15 kV, 16.7 Hz AC	high/low	3-section, 36.8 m long	mainline
-	1500 V DC	low	4-section, 42 m long	low-frequented regional line
-	1500 V DC	low	4-section, 42 m long	low-frequented regional line
TT	750 V DC / 25 kV, 50 Hz AC	low	5-section, 37 m long	middle-frequented regional line
T1	750 V DC / 25 kV, 50 Hz AC	low	4-section, 42 m long	abandoned regional line
T2	25 kV, 50 Hz AC	low	4-section, 42 m long	mainline
T11	25 kV, 50 Hz AC	low	4-section, 42 m long	newly built line
T4	750 V DC / 25 kV, 50 Hz AC	low	5-section, 37 m long + 4-section, 42 m long	middle-frequented regional line
3	750 V DC	low	3-section, 36.8 m long	high-frequented regional line
4	750 V DC	low	3-section, 36.8 m long	high-frequented regional line
S1	750 V DC / 15 kV, 16.7 Hz AC	low	3-section, 37.9 m long	mainline, abandoned regional line, middle-frequented regional line

2.2 Current existence of an urban tram system

Most of the existing tram-train systems have a functioning and branched urban tramway system as their backbone for the core city. If one excludes the systems that do not use the advantages of both modes (e. g. Lyon), using the tramway infrastructure within the city borders not only enables the passengers to reach directly their goals but also saves public costs as the most expensive and complicated urban infrastructure is either already completely built or requires only small linking adjustments. Also, the existing tramway infrastructure usually enables the operator to reduce some of the existing urban lines along the tram-train route in the city (Karlsruhe, Mulhouse). Finally, contrary to the standard regional railway in the middle-sized cities, it may serve as a welcome reinforcement for the urban tram lines in the busiest sections without the need to purchase additional urban tramcars as the tram-train units are needed anyway (Chemnitz).

Therefore, the existence of an urban tramway system is an important prerequisite for the new system introduction. The only exceptions to using both tram and train mode for a longer diametric line without existing tram systems are Saarbrücken where the newly-built tram line through the city serves as a substitution of the urban tram system and Heilbronn with its creation of the urban rail system using the existing tram-train line and vehicles from the Karlsruhe system. However efficient, the coverage and frequency needed for the urban trams may not be reached with the tram-train lines alone (see Section 3.4).

2.3 Types of suitable railway lines

Among the analyzed tram-train lines, the most frequent railway line type is a local railway with poor or even no passenger railway transport and initially questionable significance to the system. The line may be typically accustomed to a tram-train operation and upgraded so the travel time reduction effects caused by higher operational speeds, better acceleration, and direct connection to the city center can be synergic [2]. The freight transport on these lines is usually conducted only during the off-peak hours or at night. Apart from this, the tram-train units are the only vehicles on that kind of line, so its capacity does not restrict the desired tram-train operational concept.

The second type of railway line is a middle-frequented line where there is a potential for the tram-train to form the slow operation layer whereas the conventional railway vehicles serve as a fast or semi-fast train. This two-layered or zone-oriented operational scheme [3] requires a higher level of coordination between the two modes and leaves less room for modifications of the transport supply (e. g. line S5 between Karlsruhe and Pforzheim).

The last railway line type is the mainlines with operational speeds often up to 160 $km.h^{-1}$. Their use is limited as the slow tram-train units are not fully able to utilize the line speed potential and are present only when the dynamic aspect of the tram-train vehicles make a difference with the frequent stopping of the slowest operational layer (line RT5 Kassel) or when there is a railway connection to the more distant local branch line via mainline (line C15 Chemnitz, S31/S32 Karlsruhe). A special category is a newly built mainline reserved only for the tram-train operation (line T11 Paris) that denies its financial and operational advantages.

To sum up, with few exceptions in most of the listed systems the tram-train lines serve as a useful complement to both urban and regional public transport grid. In the urban area, it creates desirable enforcement for the local tram system (if applicable) and sometimes even takes over some of the urban passenger transport requirements (line S5 Karlsruhe or the Hague tram-train lines). Only if the tram-train is built as a substitution of a tram system (Saarbrücken, Paris T4) it may serve as an arterial system within the city borders. In the region, however, it can only fit into the regional railway scheme when applied to those railway lines where it can use its agility and dynamics and surpass traditional railway vehicles. As there is a very limited number of these lines in each candidate region, it is to be expected that an attempt of creating a tram-train network using each railway line according to Karlsruhe is not likely to be realized again. According to most of the analyzed lines, a new tram-train may stay an unconventional complementary way how to improve the regional railway network but even for the candidate cities, it may not form the backbone of the rail transport grid.

3 Analysis of the tram-train system operation

3.1 Travel time

As seen from Table 1, most of the lines have the overall travel time close to 60minutes whereas the average travel is 62.28 min. It covers the well-known isochrone of the daily commuting which is about an hour door-to-door travel time. The line may even exceed this value as the terminus is usually located in the suburbs after having reached the city center (Kassel, Chemnitz, Mulhouse). Only a few Karlsruhe lines have significantly higher travel time as it substitutes the regional railway on long line branches and creates an undesirable connection unattractive for commuting to the core city. On the contrary, the former Kassel line to Treysa was already closed and replaced by conventional railway as the travel time was over an hour and therefore unattractive for the commuters.

3.2 Operation frequency

Concerning the earlier mentioned complementary role of the tram-train lines in the transport system, most lines have the corresponding frequency of 30 minutes during peak hours and 60 min off-peak (or at least 60 min all the time). However, there is an exception if the systems serve as a substitution of the urban tram line accommodating an individual urban transport flow [4]. In this case, the requirements of the inner-city section are much higher and the frequency of 10 min (line S5 Karlsruhe) or even less (Saarbrücken, line T4 Paris, lines 3 and 4 in the Hague) are provided. The major disadvantage of the tram-train substituting the urban tram is the much bigger number of vehicles needed for the operational concept in the comparison with the regional line only. As the rather complicated vehicles are the most expensive part of the tram-train operation, it creates an inadequate expensive tramline in the core city.

3.3 Utilization of the tram-train advantages

Tram-train vehicles are due to their complexity more expensive than either regional railway units of the appropriate capacity or tramcars. The higher purchase price must be compensated by the utilization of its advantages over both more conventional systems. Two main tram-train operational features should be applied if the tram-train system is planned – the operation in both modes (tram and railway) and mixed operation with the railway vehicles (at least regarding the same infrastructure). However, not all the analyzed systems can fulfill that condition.

The fulfillment of the conditions is to be seen mainly by the oldest system in Karlsruhe but not with all lines as some operate only on railway infrastructure and do not have any tram sections. A good example is set by the systems in Kassel [5], Chemnitz, or Mulhouse where there is a mixed operation with both other modes and the tram-train serves as a complement to the regional network and a reinforcement of the urban tram network. In the Hague, the tram-train is in mixed operation with urban railway mode, the Rotterdam subway line E. In Saarbrücken on the line T4 in Paris with their absence of urban trams both tram and train sections are present. On the other hand, there are several cities with undesirable isolation of the system, most of which are in France. The Lyon system is operated only on refurbished railway lines, it is not connected to the city´s existing tram system and it does not bring any travel time reductions or direct connections to the city center whatsoever. A similar example can be found in Nantes where there is one short tram section with no connection to the tram system and no mixed operation with the trains and regarding the second line, the operation is conducted on mainline with no difference to the already operated regional trains. Such examples deny the tram-train system function and do not bring the desired improvements concerning the higher investment made into the vehicles or line refurbishment and may be fully substituted by cheaper regional rail.

4 Recommendations for new systems

The recommendation given in this section is based on the analysis of the current systems conducted in the previous sections. The technical parameters of the future systems correspond to the environment of the Czech Republic with its tram networks suitable for a tram-train system introduction [6] and its general principles can be used also in similar central European countries without tram-train operation (e. g. Poland or Slovakia).

4.1 Urban agglomeration size and residential structure

Although there are seven tram networks in the Czech Republic, some may be excluded in advance. The capital city of Prague is too populated, and its capacity demands cannot be satisfied by radial or diametric tram-train line. A similar situation is in Brno or Plzeň where all railway lines heading to the city are suitable for modern regional trains. However, two examples of the urban structures mentioned in Section 2.1 are to be followed. There is a compact city with the solid urban structure and prevailing radial journeys and suitable regional and middle-frequented regional lines in the Olomouc Urban Agglomeration. The Ostrava Conurbation with its industrial railways connecting different cities of its polycentric structure may serve as an example of another suitable location.

4.2 Railway line types

As the main railway lines are often busy and sufficient modern railway vehicles for the slowest operational layer are currently being introduced, it is recommended to use this kind of lines only if there is no other way how to reach the linked branch and regional lines. Even then, it is expected for the tram-train to divert from the mainline on the suburb reaching the built-up areas in tram mode and continuing to the city center. Such a concept may be implemented in the Ostrava region.

More important railway line types are the middle-frequented lines with one or two-layered operation. The dynamic tram-train vehicles may compensate for the lower speeds and the tram-train may be used in mixed operation with electric or diesel-powered long distance or semi-fast trains using the zone-oriented timetable and operating in the inner zone. This concept is suitable for example for the railway line Olomouc – Opava [7].

The most promising application of the tram-train seems to be on the poorly used or even disused regional and industrial railway lines. Due to the higher tram-train frequency, the mixed operation is expected only in off-peak or night hours and only with cargo trains. As there is the biggest freedom of operational concept that kind of lines are to be preferred in Ostrava (industrial lines heading to Orlová) and Olomouc (regional limes to Senice na Hané and Litovel).

4.3 Technical aspects

The platform height should be adjusted to the platform heights reachable in the current urban tram systems with the usual height up to 240 mm above the track level. With the usual wear and tear of the wheels considered, the acceptable urban platform height is 300 mm. In the suburban sections [8], the height should be 350 mm and if the mixed operation with passenger trains is present, the number of stations with dual platform height or separate platforms should be minimized.
All sections are to be electrified for economic, dynamic, and ecological reasons. The voltage of the tram-train system should correspond to the voltage of the tram system (600 V) and the local voltage (3 kV DC or 25 kV, 50 Hz AC) should be applied. If the conversion to the alternative current is foreseen (as it is the case with the Czech Republic and Slovakia), the AC electrification is recommended regardless of the prevailing voltage in the core city railway node.
From the vehicle categories, the 3-section 8-axle 37 m long unit is recommended as it fits into the existing tramway infrastructure and its capacity is suitable for regional lines. Also, its layout enables the separation of urban and suburban passengers.

5 Conclusion

The paper provides a very detailed and current overview of the technical characteristics of the chosen European tram-train operations. As it was experienced, a tram-train system is a rather diverse means of transport that is always uniquely adjusted to the needs of a region. Although a certain decline of the new systems was to be spotted, with the right parameters the system can utilize its advantages and complement the remaining urban and suburban public transport network. With a huge degree of adaptation to the new interoperability and ETCS regulations, the tram-train introduction will remain a support act of the more efficient and comfortable rail-based alternative which enforces the regional public transport modal split and helps to compete against the growing car ownership in the region. Appropriately created operational concept of the tram-train system, using best-practice approaches from existing operations, can thus form a very effective part of the transport system within Smart-Regions and the frequently discussed concept of Smart-Cities [9, 10].

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