A CHECKLIST FOR SUCCESSFUL APPLICATION OF TRAM-TRAIN SYSTEMS IN EUROPE

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ABSTRACT

Tram-Train systems combine the best features of streetcars with regional rail. They make direct connections between town centers and surrounding regions possible, by physically linking existing regional heavy-rail networks with urban tram-networks. The Tram-Train approach offers many advantages by using existing infrastructure to improve regional transit. However using two very different networks and mixing heavy rail and tram operations increases complexity and often requires compromise solutions.

The research surveyed existing systems to identify key requirements for successfully introducing Tram-Train systems. These requirements include network design, city layout, population density, and physical factors (e.g., platform heights). One of the most important factors is cooperation between many actors including transit operators, railways and cities. Tram-Train systems are complex, but can provide significant benefits in the right situations. The paper describes Tram-Train systems, the key requirements for successful systems and conclusions.

1. INTRODUCTION

To be successful transit must be attractive to customers and efficient to operate. Rail-based transit is efficient and attractive, but, partly due to competition from automobiles, in the 1950s many cities began removing rail track from city streets and consolidating regional rail services in stations that were inconvenient for passengers. This combination decreased transit competitiveness leading to service reductions and a downward spiral for transit in many cities.

Karlsruhe (Germany) faced a similar situation. The city's main rail station had been relocated, motorization had taken hold and transit was becoming less effective. However, transport planners had an idea: why not connect the city's tram tracks to the regional standard rail network and run through trains? These trains would use the tram tracks in the center city and the regional network in the surrounding area. After much planning the first line opened in 1992 and was a great success. Since then the approach has been successfully implemented in other cities and is sometimes called the "Karlsruhe Model" [1].

The research goal is to identify the key strategic planning factors necessary to make the Tram-Train approach successful. The research analyzed existing Tram-Train systems and reviewed transport planning theory. The result is a checklist for determining when Tram-Train systems make sense and implementation recommendations.

2. SYSTEM DEFINITION AND SCOPE

The term "Tram-Train" is a hybrid expression that has been used to define several different types of transport service. In this research, a Tram-Train system is defined as "a railway system that produces a direct connection between the regional area of a city and its town center. In the city it runs on tram tracks (partially on road space) and follows tram regulations. In the region, it runs on conventional heavy rail tracks and follows the regulations for heavy rail (with additional requirements)". This means that Tram-Train vehicles share tracks with trams in the city and with heavy rail trains on the regional tracks. One main goal of Tram-Train service is maximizing use of existing infrastructure.

Three different types of Tram-Train service were defined:

- Type A – Tram-Trains run on the tram tracks in mixed operation with conventional trams and on the heavy rail track in mixed operation with conventional heavy rail trains. Examples include Karlsruhe and Regiotram Kassel (Germany).
- Type B – describes a system in cities without an existing tram-network. Therefore the Tram-Trains do not run in mixed-operation with trams on the center city network, but do operate in mixed operation with heavy rail trains on the heavy rail tracks. An example is the Saarbahn in Saarbrucken (Germany).
- Type C – includes other systems, for example if the Tram-Train has its own exclusive tracks in the city center or the regional area and therefore does not run in mixed-operation in one

or both of these areas. Examples include the line T4 in Paris and the Randstad Rail in The Hague.

Figure 1 illustrates different types of Tram-Train systems.

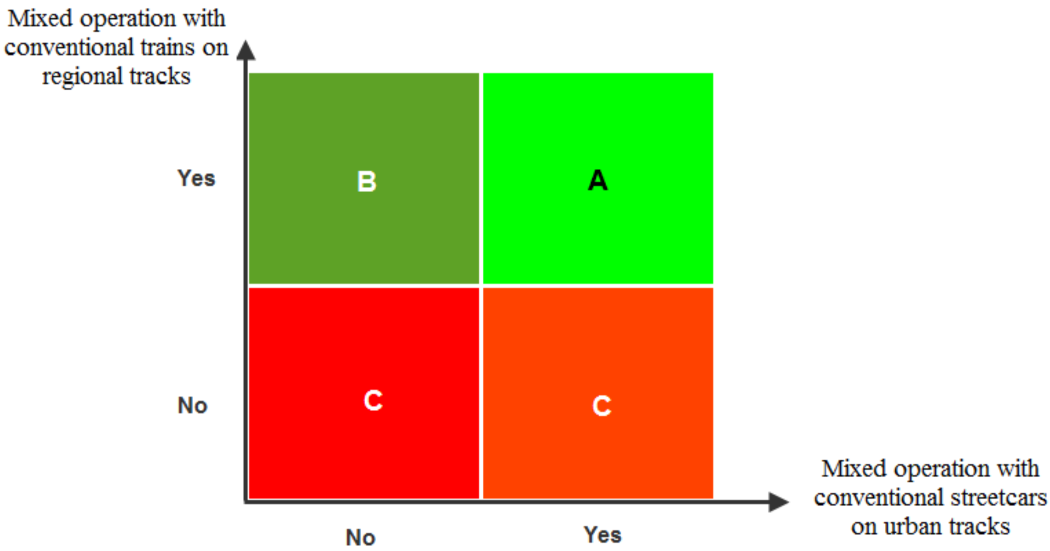

FIGURE 1 Tram-Train classification schema.

The research focus was on Tram-Train systems that share right-of-way with other forms of rail transport (types A and B), and therefore the paper only considers these systems.

3. DEMAND FOR TRAM-TRAIN-SERVICE

Travel time and comfort are two key factors influencing passenger mode choice. Unfortunately, conventional commuter rail systems in many cities lack direct links between their suburban rail network and the city center – thus requiring people to transfer between regional and urban transport-systems, reducing comfort and increasing travel times.

The Tram-Train approach is designed to solve this problem by linking urban tram and regional heavy railway infrastructure. This linkage provides a direct connection between the city-center and its suburbs helping reduce travel time and increase comfort, leading to higher patronage and efficiency. The benefit of this direct connection depends on the current situation for reaching the city center.

Since Tram-Train-systems normally operate on existing infrastructure in both the urban and rural areas, the investment costs are reduced. Furthermore the lightweight vehicles are cheaper to operate than conventional trains.

Initially, given these advantages, many believed that Tram-Train systems were the right solution for all cities with underutilized railway tracks in their suburbs. But the relatively low number of projects built since Karlsruhe's successful application shows that they may not be appropriate in every case.

Successful application of the Tram-Train approach means carefully balancing the advantages against the physical and institutional difficulties of implementing a system that connects two very different rail infrastructures.

4. RESEARCH METHODOLOGY

Figure 2 illustrates the research methodology used in this project.

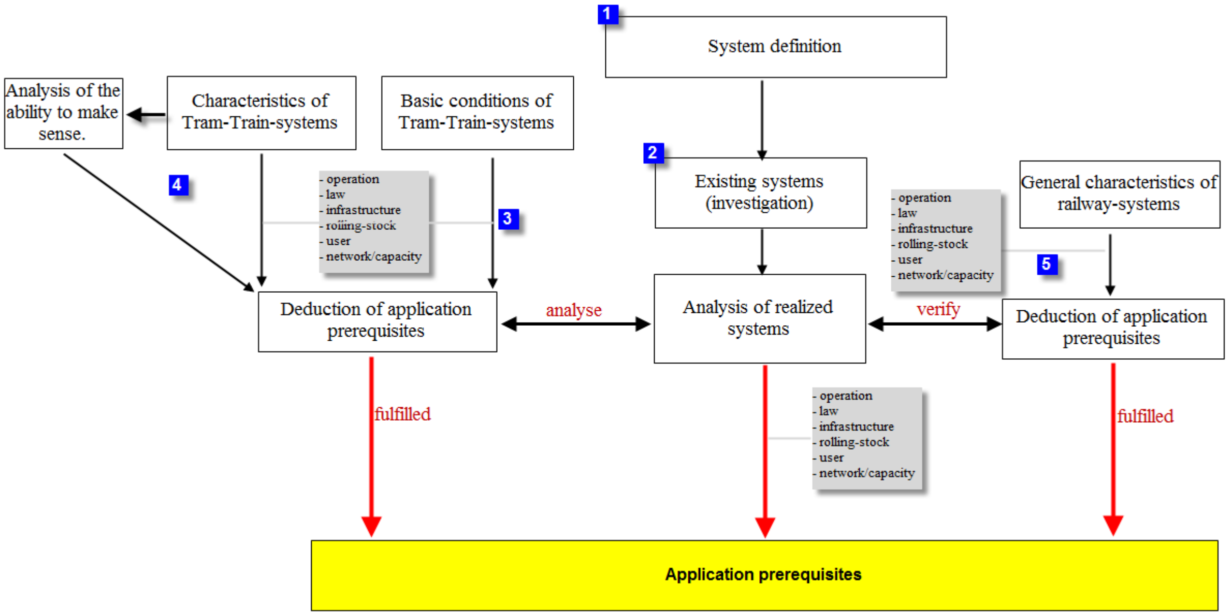

FIGURE 2 Research method.

5. HISTORY AND EXPANSION OF TRAM-TRAIN SYSTEMS

Following Karlsruhe's great success many cities implemented or considered implementing Tram-Train systems. Figure 3 shows the locations of Tram-Train systems in Europe.

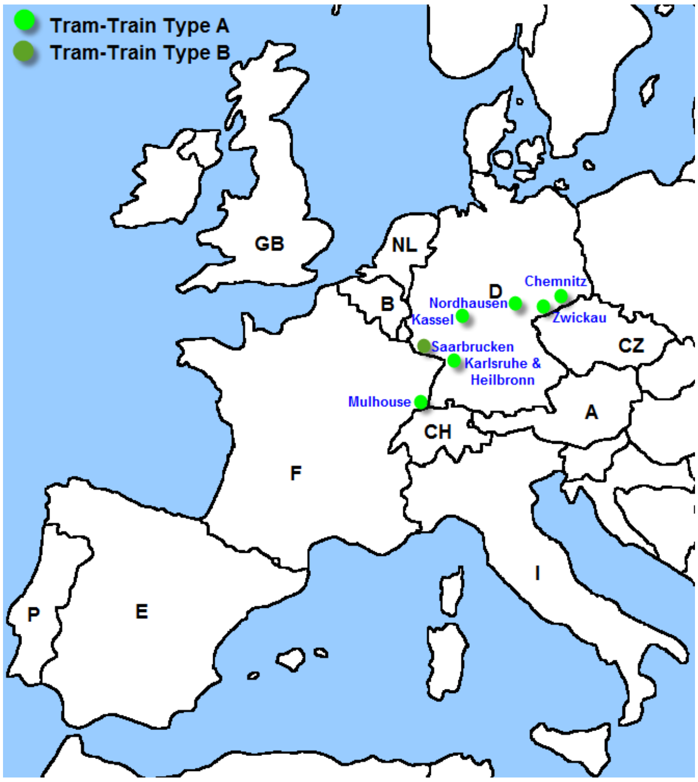

FIGURE 3 Tram-Train systems (type A&B) in Europe (map [2]).

There are several similar systems operating in the United States including the Capital Metro Rail Austin, and the Riverline in New Jersey. However under US regulations these systems operate under time separation: trams use the tracks during specified hours and standard railroad vehicles use the tracks at other times. Many US cities are interested in the Tram-Train approach, but it has been difficult to implement due to very strict rail car design requirements [3].

The history of Karlsruhe provides important clues to the success of the Tram-Train approach. Originally, the city was served by a tram-network, regional trains operated on the standard gauge German national railway and a narrow gauge private regional railway called the Albtal-railway.

In the early 1910s, Karlsruhe's main station was relocated outside the center city and the Albtal railway's terminal station was also moved to the new location. In the 1950s, this peripheral location and increasing traffic congestion on the surrounding streets made transferring between trains and trams difficult, which reduced ridership and caused increasing economic difficulties for the Albtal railway.

To avoid closing the Albtal railway, Karlsruhe decided to change it to standard gauge and connect it with the city's (standard gauged) tram-network. This provided a direct connection between town center and the suburbs, and led to a substantial increase in ridership.

After the success of the Albtal line, Karlsruhe has expanded Tram-Train service by adding through services on more regional lines. Today, the network has a length of approximately 500 km (311 mi) [1], [4] [5].

Interestingly, since ridership is so high, Karlsruhe recently decided to build a tunnel under its center to increase capacity and reduce the impact of Tram-Train vehicles on the city’s popular pedestrian area [6].

The history of the Tram-Train system in Karlsruhe provides some preliminary lessons on conditions that make such systems successful. The next sections outline these conditions.

FIGURE 4 City center Karlsruhe (left); Regiotram Kassel meets heavy rail (right) [7].

6. KEY FACTORS FOR SUCCESSFUL TRAM-TRAIN SYSTEMS

6.1 Basic Conditions

6.1.1 Speed and Network Coverage

The maximum speed of Tram-Train vehicles depends on physical characteristics and safety requirements. Tram-Train vehicles have much lower body stiffness than standard heavy rail vehicles and do not meet the UIC stiffness requirements [8]. This reduces the passive safety in a crash situation. (Stiffness is referred to as “buff strength” in the United States.)

With reduced passive safety in the railcars, the system’s active safety must be increased to reach an acceptable level of safety in mixed operations. Therefore special rules for mixed operation must be followed (“LNT-guidelines” / guidelines for lightweight rapid transit railcars). These rules were published in Germany after implementation of Karlsruhe’s system. The rules set the maximum speed for Tram-Train-vehicles at 90 km/h (56 mph) (or 100 km/h (62 mph) if additional requirements are satisfied) [8].

The average speed of a Tram-Train system is around 35-45 km/h (22-28 mph), because the system combines features of conventional regional trains and trams. Since people generally have a fixed travel time budget, a transit line's average speed helps determine its effective network coverage. Assuming that the maximum commuting time per day and direction is one hour, then the maximum system radius is approximately 35-45 km (22-28 mi) from the city center.

6.1.2 Capacity and Capability

In center cities the Tram-Trains operate on streets and interact with other vehicles. Therefore they are subject to the same regulations as trams. The German "Bau- und Betriebsordnung für Strassenbahnen (BOStrab)" regulations are a typical example [9]. According to BOStrab the maximum dimensions of Tram-Train-vehicles are 75 m (246 ft) long and 2.65 m (8.7 ft) wide. Other countries have similar maximum dimensions.

Considering passenger comfort, a Tram-Train-vehicle's capacity is about 112 passengers (based on occupying 95% of seats and 20% of standing room) [10]. When these vehicles are operated in double traction (to reach the allowed maximum length of 75 m) the capacity is about 225 passengers. A typical example is the Alstom Regio Citadis illustrated in Figure 4.

In the suburbs, the operating capacity on the heavy rail track is limited by the other traffic and technical design of the tracks. Assuming that the maximum frequency of the Tram-Trains is 10 minutes (considering factors such as available slots on heavy rail tracks, infrastructure capacity, etc.), then the maximum traffic load profile for the system is about 1,400 passengers per hour and direction. A Tram-Train system type A&B can therefore not be applied on lines expected to serve very high passenger volumes. A Tram-Train system of type C, which uses separated independent tracks in the region can provide more capacity.

6.2 City Characteristics

6.2.1 City Size

Most of the European cities where Tram-Train systems have been successfully implemented have populations from 100,000 to 300,000. The typical Tram-Train-city functions as a regional metropolis and the surrounding region is strongly oriented to the city for employment, shopping, recreational facilities, hospitals, government and higher education. This centralizes traffic flows between the city center and surrounding areas.

Often these cities are too small to provide standard regional rail service (i.e., which requires transferring to local transit at a central station), since passenger volumes on specific corridors are too low.

The combination of lower costs (due to lower capacity requirements) and more attractiveness (due to direct central city service) make these markets very attractive for Tram-Train systems.

A type A Tram-Train system is possible in cities with an existing tram-network (many European cities with 100,000-200,000 inhabitants still have tram networks). In cities without existing tram-networks a type B Tram-Train system could be introduced by building a new tram track in the center city. In this case the regional connection means that more passengers can be attracted to the city tram and justify construction of the new track. This is well illustrated in the city of Saarbrucken (Germany).

Countries outside Europe have different city size benchmarks depending on existing transit use patterns. For example, the Capital Metro Rail of Austin serves a city of approximately 800,000 people [11].

6.2.2 Existence of suitable Center City Tram Corridors

An important success factor for Tram-Train systems is the existence of a suitable corridor for operating Tram-Trains from the heavy rail track to the city center. Most importantly this corridor must have a good connection and offer adequate space. Since Tram-Train vehicles are often larger than city trams the corridor must be wide enough.

Furthermore, the track should have as much exclusive right of way as possible to provide high reliability. Reliability is especially important for Tram-Trains since they are assigned specific slots on the heavy rail network. If Tram-Trains are not reliable, they interfere with regular railway operations or have to wait for the next available slot. In the case of a type B Tram-Train, the selected corridor must have adequate space for building a new tram line and ensuring that it can be operated reliably.

Another important consideration for the center city tram corridor is capacity to operate Tram-Trains. If traffic on these corridors is already high, adding Tram-Trains with longer vehicle lengths than existing trams can be difficult and controversial. This is even true in transit malls or pedestrian zones where Tram-Trains can block pedestrian flows and traffic on cross streets. Therefore the corridor must be very carefully designed.

6.2.3 Activity Centers

Providing a direct connection to the city center only makes sense if there is sufficient transport demand (in other words most suburban passengers are going to the town center). If the traffic flows are dispersed throughout the city, a Tram-Train-line will not serve many passengers and a conventional radial tram-network might be a better option.

Therefore the most suitable cities for Tram-Train systems have a distinct main town center with a high level of activity including employment, shopping and educational institutions. Alternatively, the city could have several sub-centers but these would need to be served efficiently with the same central city tram track. Having both a high activity center and smaller sub-centers along the route is the best possible situation.

This criterion is related to city size: cities with a pronounced main center are often medium-sized (100,000-300,000 inhabitants). These cities often have a city center with a high density of activity but are too small to have several separate activity centers.

Figure 5 illustrates a typical corridor in Karlsruhe and the town center of Kassel.

FIGURE 5 Corridor between town center and railway station in Karlsruhe (left); city center of Kassel (right) [7].

Finally, it should be noted that the Tram-Train line could also positively influence center city development. For example, in Karlsruhe approximately 300 new shops opened in the city center between 2003 and 2006 [12].

6.2.4 Distance between Railway Station and Activity Centers

A key factor for Tram-Train systems is the distance between the heavy rail station and the city center.

If a city’s main activity center is located near the railway station, a direct connection via Tram-Train does not produce much additional benefit: people can already reach the center by foot and do not have to take the tram.

On the other hand, a Tram-Train can be very beneficial if the city’s main activity center is located farther away from the railway station (many railway stations are located outside the city center, and many railway stations in smaller cities are being moved further outside of the city to better connect with high speed rail lines that divert around these smaller cities). In this case the railway station is located far enough away that people would normally take a tram or bus to the city center (e.g., > 1 km (0.62 mi) or 10-15 minutes walking time).

As part of this research the distance between the railway station and the town center in existing Tram-Train-cities was measured using Google-maps and confirmed in field visits. Table 1 summarizes the results of these surveys.

TABLE 1 Distance between Railway-Station and Town Center (Center of Activity) and Estimated Walking Time

(a) Cities with Tram-Train systems

City	*Distance*[a] *[m]*	*Time [min]*
Karlsruhe	1900	24
Zwickau	1800	22
Chemnitz	1100	14
Kassel	700	12
Mulhouse	1000	12
Saarbrucken	800	10
The Hague	1000	12
Heilbronn	1100	13
(Austin)	1800	22

(Kassel: different elevation above sea level; distance to Kassel Wilhelmshöhe > 2 km)
(Austin: similar system)

(b) Cities currently or formerly planning Tram-Train-projects

City	*Distance*[a] *[m]*	*Time [min]*
Nantes	1400	17
Leiden	>1000	12
Adelaide	1100	14
Braunschweig*	2100	26
Strasbourg*	1000	12
Rostock*	1700	21
Lubeck*	1300	16
Kiel*	1100	14
Bordeaux	2500	30
Grenoble*	1100	13

(* Project considered but rejected/postponed due to lack of funds / alternatives)

(c) Comparable Cities but without Tram-Train-projects

City	*Distance*[a] *[m]*	*Time [min]*
Mannheim	800	10
Hannover	750	8
Augsburg	750	9
Magdeburg	600	7
Hagen	300	4
Leverkusen	200	2
Oberhausen	500	6
Osnabruck	800	10
Mainz	900	11
Hamm	750	9

Cities with Tram-Train systems (part (a) on Table 1) have railway stations located away from the city center or at a different elevation (walking time normally > 10 minutes). The cities currently planning or which previously considered Tram-Train-projects (b) show the same conditions. Cities without a Tram-Train or planned projects (c) have relatively short distances between the railway station and town center.

The distance between the railway station and town center is a key indicator of the benefit offered by a direct Tram-Train connection. This applies especially for type A Tram-Train systems. For type B systems one of the main incentives is to stimulate the reintroduction of urban tram service (e.g., Saarbrucken) so the distance between station and city center is not as important.

6.3 Regional Characteristics

6.3.1 Orientation to the City

A key success factor for Tram-Train systems is strong regional orientation towards the center city. This means that the suburban areas should feature largely housing and most of the regional population should work and shop in the city, focusing traffic flow towards the center. If there are other large activity centers or cities nearby (as is often the case in large metropolitan areas), the

[a] 1,000 m = 0.62 mi

regional traffic flows would be more dispersed and therefore more difficult to serve with a Tram-Train system.

6.3.2 Population Density

The Tram-Train system is a hybrid suburban transit system serving a niche between buses and regional rail. Since Tram-Train vehicles operate on city streets their capacity is limited. Therefore, the population density should not be too high or the system will have insufficient capacity to meet demand. If the density is too low, a Tram-Train system is also inappropriate.

The researchers estimated population density on existing German Tram-Train lines to develop density criteria for Tram-Train systems. Population density was calculated by summing the number of people who lived around each station for the entire line (the catchment area of a station was assumed to be 750 meters (approx. ½ mile)) and dividing by the length of the line. This provided a population density per linear km of corridor length. Table 2 summarizes the results. Note this only includes the suburban sections of the Tram-Train route (i.e., the portions operated on the heavy rail network).

TABLE 2 Population Density and Reachable Inhabitants along Tram-Train-Line Corridors in Germany

Regional Track	Length [km]	Reachable Inhabitants	Persons/km	Frequency [min]
Saarbrucken Brebach-Sarreguemines	14	27,400	1,960	30
Saarbucken Malstatt-Walpershofen	8	19,100	2,390	15
Saarbrucken Malstatt-Limbach	19	39,400	2,080	15
RT3 Kassel Vellmar-Warburg	36	35,000	980	30
RT4 Kassel Oberzwehren-Wolfhagen	25	29,400	1,180	60
RT5 Kassel Oberzwehren-Melsungen	20	30,000	1,500	60
RT9 Kassel Vellmar-Treysa	52 *	47,000	900	60
550 Chemnitz-Stollberg	16	26,100	1,630	30
Zwickau Maxhuette-Zwotental	48	36,100	750	60
Zwickau Maxhuettte-Plauen	40	46,200	1,160	60
S1 north, Hochstetten-Karlsruhe Neureut	11	27,300	2,480	20
S1 south, Karlsruhe-Rupuerr-Bad Herrenalb	18	42,100	2,340	30
(* >45 km)				

The number of persons per kilometer (p/km) provides an index about the population density in the region, but this value cannot be considered alone. For example, a Tram-Train-line with a length of 45 km could not serve a density of 2,500 p/km since it would have insufficient capacity. Therefore it is also necessary to consider the absolute number of inhabitants along the entire line.

The researchers also calculated this for existing German Tram-Train corridors. The results show that the number of reachable inhabitants lies between 19,000 and 47,000 persons, but is mostly around 25,000-35,000.

Finally, it is also important to consider the standard gravity model indicating that the number of passengers increases towards the center of activity. This means that, in areas with equal population densities, more people will use the Tram-Train system from stations near the center than farther away from the center.

In summary, Table 2 shows that a population density of approximately 2,500 p/km is normally combined with a number of reachable inhabitants of 20,000-30,000 for a short corridor, while longer corridors with lower population densities (750-1500 p/km) can serve areas with up to 50,000 reachable persons. It should be emphasized that these rules of thumb are very closely tied to local conditions such as modal-split characteristics and specific operating characteristics of the Tram-Train service. Therefore these values should only be considered as benchmarks for a rough analysis.

If the distance between stations is approximately 1-2 km, lightweight Tram-Train-rolling stock can be used. These vehicles can accelerate fast and their energy consumption is lower than conventional trains. Generally the Tram-Trains stop at all stations on the rail line and inner city tram tracks. Having the tram-trains stop at all stations makes it possible to use true regional trains to provide express service on the same line. The subject of station spacing and stopping patterns for Tram-Train systems is an excellent topic for further research.

6.4 Technical Issues

6.4.1 System Change Area and accessible Network

Since type A and B Tram-Train vehicles operate on both the city tram network and the standard gauge railway network, they need to be designed to operate using two different types of power supply, signaling systems, physical profiles etc. Consequently the Tram-Train rolling stock is generally more complex and expensive than standard trams or comparable regional rail trains.

One aspect of operating using different systems is that a particular place where the Tram-Train vehicles change from the tram track to the heavy rail track is necessary. At this point power supply changes, a different rail profile is applied, and different rules and regulations must be followed (e.g. other safety standards).

The ease of making the changeover between the railway and tram networks is important for determining Tram-Train system feasibility. The first requirement is that there must be a suitable physical location where the networks can be connected. This means physical proximity and sufficient space for the transition infrastructure.

An important factor in Tram-Train system success is the extent of the network that can be reached with a single changeover area. The best case is when it is possible to reach the whole heavy rail network with just one interface. In contrast, if several changeover areas are needed and/or several different power systems are used on the heavy rail system, the situation is not optimal. Therefore, a good indicator of Tram-Train system feasibility is the ratio between ease of building the changeover area and the reachable network.

All the existing Tram-Train systems in Germany have a good ratio of these factors. In Zwickau for example, the system uses an old siding track at the main station. In Karlsruhe the Albtal railway terminal was located directly adjacent to the city tram tracks and could be rebuilt quite easily into a through station for Tram-Trains (Figure 6).

FIGURE 6 Karlsruhe Albtal-railway-station [7].

6.4.2 Existing Tram and Heavy Rail Track Technical Standards

The technical standards of the existing tram and heavy rail systems have a significant influence on the ease of implementing a Tram-Train system. The main advantage of Tram-Train systems is that they can operate on existing infrastructure, if large infrastructure investments are needed, then the cost benefit ratio for a Tram-Train system is reduced.

Some key technical standards that help determine feasibility include handicapped accessibility, platform heights, the gap between rolling-stock and platform, structure gauges and rail profiles. Tram-Train vehicles must be able to operate on both the existing tram and heavy-rail stations and track. If the networks are incompatible, the system needs new infrastructure. Examples include new station platforms or third rails in the case of rail gauge differences. In both cases the new infrastructure will increase capital costs and operating complexity. In Zwickau, where the inner-city track is quite short, a three-rail track was an acceptable solution.

The power system changeover is a good example of the complexity involved in changing between the standard railway and the tram network. Normally the electric power supply changes, for example from 750V tram system to 15 kV 16.7 Hz AC or diesel. This difference is generally addressed by using dual mode Tram-Train vehicles. However, it is also possible that a region can have several types of power used on the standard gauge rail lines. For example, in Kassel the Tram-Train system uses two different types of dual-system rolling stock (electric/electric, electric/diesel). In this case the added complexity of having two types of rolling stock was less than the cost of electrifying the rail line. In Saarbrucken (a German border city where it might be possible to extend lines on both the German and French national rail networks), the decision to build a Tram-Train system was likely made more to support reintroduction of the tram since the three different electrical power systems will make future extensions complicated.

The important point is that planners must carefully consider how the infrastructure and rolling stock will work together when considering the feasibility of a Tram-Train system. More complex systems reduce feasibility.

6.5 Quality of Existing Connections

The benefit of a direct connection depends on the current situation for reaching the city center. If the railway station is near the city center there is little need for a Tram-Train system, because regional rail passengers can simply walk to the city center.

If passengers need to transfer between regional trains and inner-city transport systems, planners must consider specific qualities of the transfer process including distance, level changes, and scheduling. The main criterion is transfer time. If there is a good and fast existing connection with a harmonized timetable, the benefit of a Tram-Train system will be limited. If there is a bad connection, the benefit of a Tram-Train system can be high, reducing travel time and increasing comfort and passenger demand.

Therefore an important part of analyzing the benefit of a Tram-Train system is evaluating the possibilities for improving the existing transfer between regional rail and city transit. Karlsruhe's experience is typical: the Albtal-railway station and the main station were quite far from the city center and transfer conditions were poor. Directly connecting the regional lines to the tram network was shown to be the best solution.

6.6 Institutional Complexity

In addition to being technically complex, Tram-Train systems are institutionally complex. The service operates in both cities and suburban areas – two different areas, with somewhat different interests. On an operations level, the vehicles run on several different track infrastructures with (generally) different owners and other operators. This means, for example, that train drivers must be trained on several networks. It is easy to see that the system involves many actors all with their own interests. Furthermore, in addition to different transportation actors, a Tram-Train system can only be realized in coordination with cooperative city planning.

Implementing such a complex system requires very good cooperation between the different actors. Finding common ground can be difficult, but is essential.

An important factor in the development of Tram-Train systems is prior experience. If a country has experience in planning Tram-Train systems it has experts in this domain and a legal basis for proceeding. This assists and accelerates Tram-Train-projects. This effect is shown clearly in Germany and France, where many new projects were started after the first system was realized.

As outlined above, even though a Tram-Train system uses existing infrastructure sometimes the investment cost can be high (depending on the existing technical conditions). Therefore, Tram-

Train systems need to have a certain "level of support" in the city for transit including financial resources. Many Tram-Train projects have been rejected due to lack of funds and/or political support.

6.7 Strategic Planning

Thinking strategically is important when planning a Tram-Train system. For example, planners should carefully compare Tram-Train systems to other solutions including alternatives such as extensions of existing systems and improving transfer possibilities at the railway station serving regional trains. Both are good ways to achieve similar benefits at lower costs. It is also important to consider how the Tram-Train system fits into the long range city/regional transport plan.

Strasbourg is an excellent example. The city originally intended to extend its existing tram network in a first step and then connect it with the regional standard rail network in a second step. Since the project required a very expensive tunnel for the system change area, it was postponed several times. Instead, Strasbourg decided to improve the transfer conditions at the railway station and make further extension to the city tram system.

7. CHECKLIST

The research goal was to develop a checklist for identifying optimal conditions for Tram-Train systems. This checklist was developed using the factors discussed in the foregoing sections. The checklist provides a rough analysis tool for planners to evaluate whether a city is suitable for a Tram-Train system. Table 3 presents the checklist.

Each criterion on the list should be evaluated on a sliding scale (for example 1-5 points). If, using the checklist criteria, a city seems suitable for introduction of a Tram-Train system, then a more detailed analysis should be completed. The first aspect of this detailed analysis is capacity. In analyzing capacity it is important to take into account that the higher level of comfort and the shorter travel time provided by a Tram-Train system can significantly increase the passenger volume.

TABLE 3 Checklist for Possible Tram-Train-Cities

	Characteristics of the Cities
1	Size of the city
2	Regional metropolis
3	Existence of a suitable tram-corridor
4	Conversion of the corridor (monument conservation?) (only for type B)
5	City too small for tram network/ bus used to capacity (type B)
6	Existence of a main center of activity
7	Further smaller centers of activity along the line
8	Distance between railway station and center of activity
	Characteristics of the Region
9	Orientation to the city (rural metropolis)
10	Settlement structure/ structure type of the region
11	Settlement structure along the heavy rail (size, distance betw. villages)
12	Population density and reachable inhabitants
13	Possibility to connect a bigger city at the end of the deployment radius
	Infrastructure and Technic
14	Existence of a suitable corridor/elementariness for power system change area
15	Ratio between costs and reachable network
16	Platform heights (tram/heavy rail), complexity for handicapped accessibility (for type A)
17	Technical parameters of the heavy rail tracks (equipment, decision between special rolling stock or conversion of the track)
18	Technical parameters of the existing tram (gauge) (for type A)
19	Possibility for dividing the project in several stages
	Existing Connections
21	Existing connections (quality, travel time, comparisons)
21	Completion to the overall system
22	Capacity on the tracks with today's connections
23	Capacity on the crossroads/stations with today's connections
24	Circumstances of transfer process train/tram
	Institutional Circumstances
25	Situation of the railway/tram companies (financial situation, organizational structure)
26	Cooperation between city and regional area
27	Politics/ strategy of the city
28	Financial situation of city and region
29	Position of state adverse projects (financial support)
30	Regulatory situation
31	Experience of the country with Tram-Train-projects
	Further Prerequisites
32	Acceptance (especially traffic in the city center)
33	Existing development plans
34	Rough comparisons with possible alternatives: Costs and benefits
35	(Other application areas, for example tangential connections (Tram-Train Paris))
	Basic Conditions
36	Capacity and capability (verification)

8. DISCUSSION

Tram-Train systems can be excellent additions to transit in many cities, however they require particular conditions to be successful. The goal of this research was to identify those conditions.

Tram-Train systems involve mixed operations on tram and standard heavy rail tracks. This mixed operation and the many interfaces it creates, increases complexity and sometimes requires compromise solutions and changes to the existing networks. Furthermore, although Tram-Train systems are designed to operate on existing infrastructure, they can be difficult and expensive to implement. It’s important to note that solutions found today in Karlsruhe or Kassel (inadequate handicapped accessibility) will not be accepted in future systems, thereby increasing complexity and costs.

Successfully introducing a Tram-Train system requires extraordinary good cooperation between many stakeholders. This requires time and good institutional cooperation. Tram-Train-planning must be integrated in the city and regional planning.

Under the right circumstances, Tram-Train systems can be very beneficial, increasing the number of transit passengers and improving the modal-split. Providing a direct connection to the city center increases comfort and reduces travel time. On the other hand, a good conventional regional rail system without a direct connection but with good transfer conditions and a well-coordinated schedule can also offer comfortable and fast connections.

A Tram-Train system can become the victim of its own success if ridership becomes too high. The system can quickly reach its capacity limit (a particular problem due to limited vehicle length). Operating trains more frequently can increase capacity, but increases operational costs and congestion in center cities and may not be possible due to a lack of capacity on the standard rail network. European experience shows that Tram-Trains can cause considerable disruption in central pedestrian zones, therefore very low headways may not be accepted. Expensive tunnels under the city center then become necessary, as the situation in Karlsruhe shows.

The checklist developed as part of this research allows planners to make a rough assessment of whether a Tram-Train could be a good option for a city. Carefully considering these factors early in the planning process could help reduce the number of unrealistic projects and save time.

The number of Tram-Train projects in planning or under construction shows that the expansion of this hybrid transit mode is not over. There are still cities that offer great conditions for a Tram-Train system. In short, Tram-Train systems have a future.

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