Checklist for Successful Application of Tram–Train Systems in Europe

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Tram–train systems combine the best features of streetcars with regional rail. These systems 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, the use of two dissimilar networks and the mixing of heavy rail and tram operations increase complexity and often require compromise solutions. The research surveyed existing systems to identify requirements for successfully introducing tram–train systems. The 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.

To be successful, transit must be attractive to customers and efficient to operate. Rail-based transit is efficient and attractive, but, partly because of 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. These actions decreased transit competitiveness, which led 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? The 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 success. Since then, the approach has been successfully implemented in other cities and is sometimes called the Karlsruhe model (*1*).

The research goal was to identify the strategic planning factors necessary for making the tram–train approach successful. The research analyzed current tram–train systems and reviewed transport planning theory. The result was a checklist for determining when tram–train systems make sense and implementation recommendations.

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SYSTEM DEFINITION AND SCOPE

The term "tram–train" is a hybrid expression that has been used to define several 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 the use of existing infrastructure.

Three 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. The tram–trains do not run in mixed operation with trams on the center city network; instead, they run in mixed operation with heavy rail trains on the heavy rail tracks. An example is the Saarbahn in Saarbrücken, Germany.
- Type C includes other systems, for example, those in which 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, Netherlands.

Figure 1 illustrates the 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 considers these systems only.

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. People are thus required to transfer between regional and urban transport systems, which reduces comfort and increases travel times.

The tram–train approach is designed to solve this problem by linking urban tram and regional heavy railway infrastructure. The linkage

FIGURE 1 Tram–train classification schema.

provides a direct connection between the city center and its suburbs, which helps reduce travel time and increase comfort and thus leads 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 urban and rural areas, investment costs are reduced. Furthermore, the lightweight vehicles are cheaper to operate than are conventional trains.

Initially, given these advantages, many believed that tram–train systems were the right solution for all cities with underused railway tracks in their suburbs. However, the small 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 dissimilar rail infrastructures.

Figure 2 illustrates the research methodology used in this project.

HISTORY AND EXPANSION OF TRAM–TRAIN SYSTEMS

After Karlsruhe's success, many cities implemented or considered implementing tram–train systems. Figure 3 shows the locations of tram–train systems in Europe.

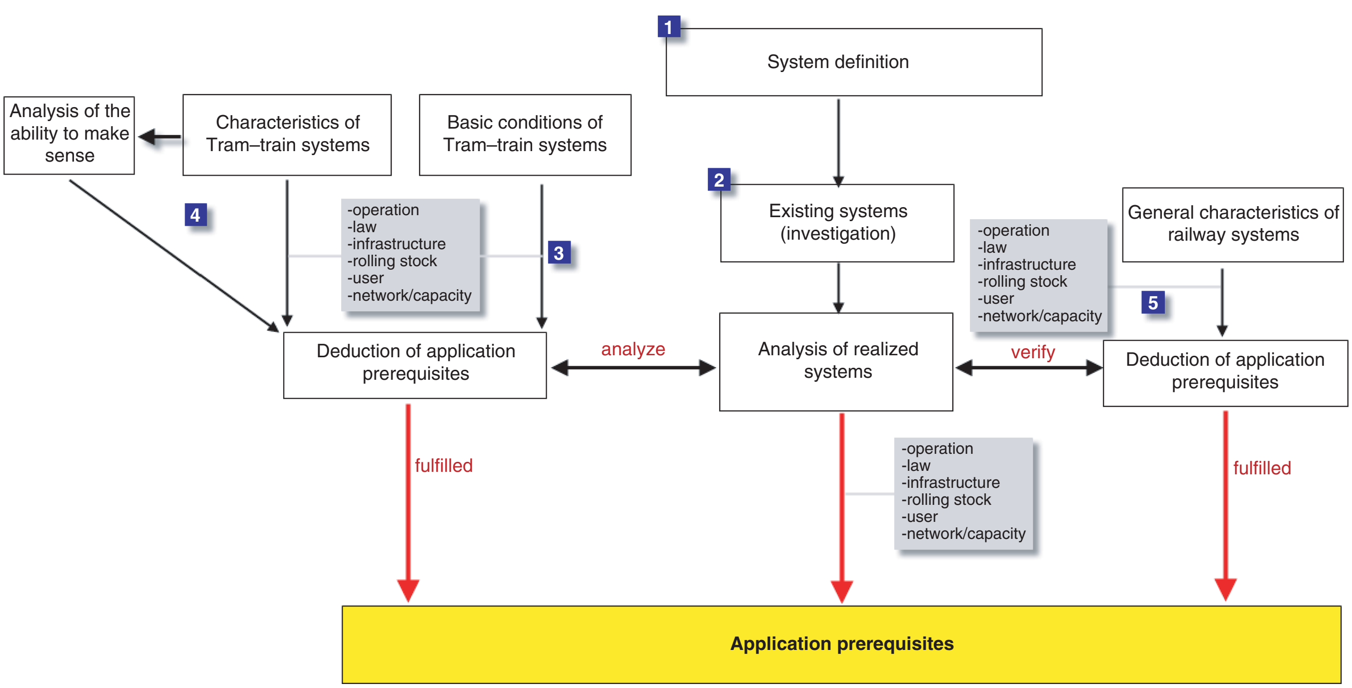

FIGURE 2 Research method.

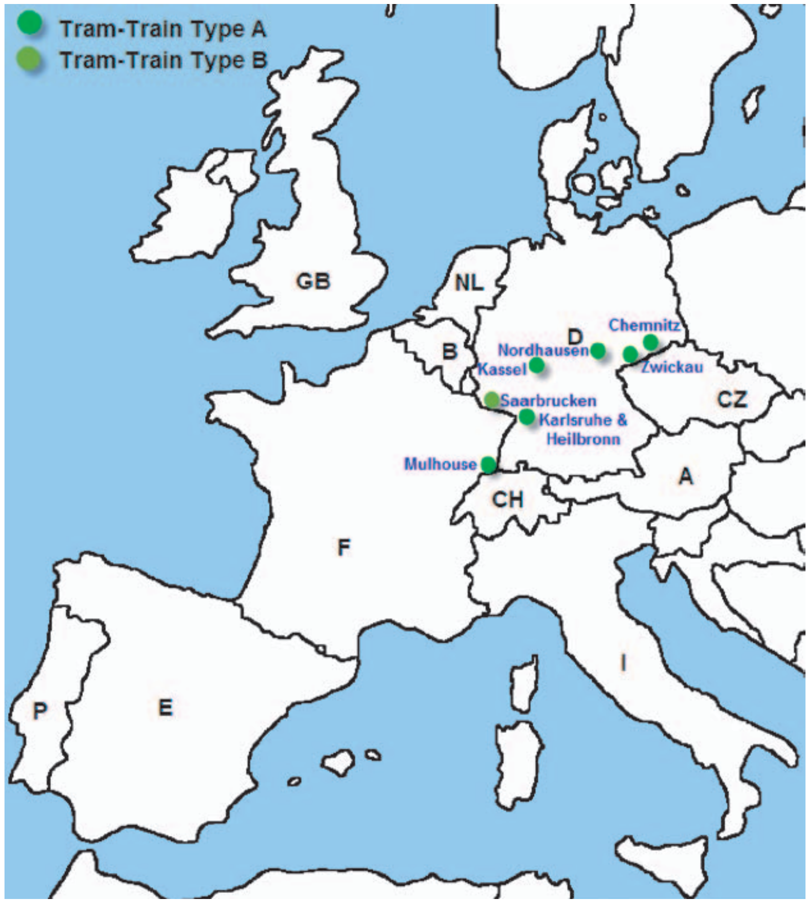

FIGURE 3 Tram–train systems (Types A and B) in Europe. (Map background: blank digital map of Europe, http://www.youreuropemap.com.)

Several similar systems operate in the United States, including the Capital MetroRail in Austin, Texas, and the River Line in New Jersey. However, under U.S. 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 U.S. cities are interested in the tram–train approach, but it has been difficult to implement because of strict rail car design requirements (*2*).

The history of Karlsruhe provides important clues concerning the success of the tram–train approach. Originally, the city was served by a tram network. Regional trains operated on the standard-gage German national railway and a narrow-gage 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 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 economic difficulties for the Albtal railway.

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

With 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; 3; 4,* pp. 14–15). Because 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 (*5*).

The history of the tram–train system in Karlsruhe provides preliminary lessons on conditions that make such systems successful. The next sections outline these conditions (see Figure 4).

KEY FACTORS FOR SUCCESSFUL TRAM–TRAIN SYSTEMS

Basic Conditions

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 International Union of Railways stiffness requirements (*6*). 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 rail cars, the system's active safety must be increased to reach an acceptable level of safety in mixed

(a) (b)

FIGURE 4 Tram–train systems: (*a*) Karlsruhe city center and (*b*) RegioTram Kassel meets heavy rail. (Photographs: L. Naegeli, 2010.)

operations. Therefore, special rules for mixed operation must be followed (guidelines for lightweight rapid transit rail cars). 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] (*6*).

The average speed of a tram–train system is 35 to 45 km/h (22 to 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. On the assumption that the maximum commuting time per day and direction is 1 h, the maximum system radius is 35 to 45 km (22 to 28 mi) from the city center.

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 (*7*). According to BOStrab, the maximum dimensions of tram–train vehicles are 75 m (246 ft) in length and 2.65 m (8.7 ft) in width. Other countries have similar maximum dimensions.

With regard to passenger comfort, a tram–train vehicle's capacity is about 112 passengers (based on occupying 95% of seats and 20% of standing room) (*8*). 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, which is shown in Figure 4.

In the suburbs, operating capacity on heavy rail track is limited by the other traffic and the technical design of the tracks. If the maximum frequency of the tram–train is 10 min (on the basis of factors such as available slots on heavy rail tracks and infrastructure capacity), the maximum traffic load profile for the system is about 1,400 passengers per hour per direction. A tram–train system of Type A or B therefore cannot be applied on lines expected to serve high passenger volumes. A tram–train system of Type C, which uses separated independent tracks in the region, can provide more capacity.

City Characteristics

City Size

Most of the European cities where tram–train systems have been successfully implemented have populations between 100,000 and 300,000. The typical tram–train city functions as a regional metropolis, and the surrounding region is strongly oriented toward 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 (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) makes these markets 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 to 200,000 inhabitants still have tram networks). In cities without a tram network, 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, which would justify construction of the new track. This is well illustrated in Saarbrücken.

Countries outside Europe have different city size benchmarks depending on transit use patterns. For example, Capital MetroRail of Austin serves a city of approximately 800,000 people (*9*).

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. The most important consideration is that the corridor 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 must 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 vehicles longer 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 carefully designed.

Activity Centers

Providing a direct connection to the city center is useful only if there is sufficient transport demand (i.e., most suburban passengers are going to the town center). If 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 subcenters, but they would need to be served efficiently with the same central city tram track. Having both a center with high activity and smaller subcenters along the route is the best possible situation.

This criterion is related to city size: cities with a pronounced main center are often of medium size (100,000 to 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 shows a typical corridor in Karlsruhe and the town center of Kassel.

Finally, 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 (*10,* p. 7).

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 on foot and do not have to take the tram. In contrast, a tram–train can be 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 farther outside of the city to provide better connections 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., more than 1 km (0.62 mi), or 10 to 15 min walking time].

As part of this research, the distance between the railway station and the town center in existing tram–train cities was measured by

(a) **(b)**

FIGURE 5 Typical corridor (*a*) between town center and railway station in Karlsruhe and (*b*) in city center of Kassel. (Photographs: L. Naegeli, 2010.)

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

City	Distance (m)	Time (min)
Cities with Tram–Train Systems		
Karlsruhe, Germany	1,900	24
Zwickau, Germany	1,800	22
Chemnitz, Germany	1,100	14
Kassel, Germany[a]	700	12
Mulhouse, France	1,000	12
Saarbrucken, Germany	800	10
The Hague, Netherlands	1,000	12
Heilbronn, Germany	1,100	13
Austin, Texas[b]	1,800	22
Cities Currently or Formerly Planning Tram–Train Projects		
Nantes, France	1,400	17
Leiden, Germany	>1,000	12
Adelaide, Australia	1,100	14
Braunschweig, Germany[c]	2,100	26
Strasbourg, France[c]	1,000	12
Rostock, Germany[c]	1,700	21
Lubeck, Germany[c]	1,300	16
Kiel, Germany[c]	1,100	14
Bordeaux, France	2,500	30
Grenoble, France[c]	1,100	13
Comparable Cities but Without Tram–Train Projects		
Mannheim, Germany	800	10
Hannover, Germany	750	8
Augsburg, Germany	750	9
Magdeburg, Germany	600	7
Hagen, Germany	300	4
Leverkusen, Germany	200	2
Oberhausen, Germany	500	6
Osnabruck, Germany	800	10
Mainz, Germany	900	11
Hamm, Germany	750	9

NOTE: 1,000 m = 0.62 mi.
[a]Kassel: different elevation above sea level; distance to Kassel Wilhelmshöhe > 2 km.
[b]Austin: similar system.
[c]Project considered but rejected or postponed due to lack of funds or alternatives.

using Google Maps and confirmed in field visits. Table 1 summarizes the results of these surveys.

Cities with tram–train systems (the left-hand part of Table 1) have railway stations located away from the city center or at a different elevation (walking time normally more than 10 min). Cities currently planning or that previously considered tram–train projects (the middle part of the table) show the same conditions. Cities without a tram–train or planned projects (the right-hand part of the table) have relatively short distances between the railway station and the town center.

The distance between the railway station and the town center is an 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., Saarbrücken), so the distance between station and city center is not as important.

Regional Characteristics

Orientation to the City

A key success factor for tram–train systems is strong regional orientation toward the center city. This means that the suburban areas should largely feature housing and that most of the regional population should work and shop in the city, focusing traffic flow toward the center. If there are other large activity centers or cities nearby (as is often the case in large metropolitan areas), the regional traffic flows would be more dispersed and therefore more difficult to serve with a tram–train system.

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.

Population density was estimated on 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 m (approximately ½ mi)] and dividing by the length of the line. This procedure provided a population density per linear kilometer of corridor length. Table 2 summarizes the results. This includes only the suburban sections of the tram–train route (i.e., the portions operated on the heavy rail network).

The number of persons per kilometer provides an index of 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 persons per kilometer since it would have insufficient capacity. Therefore, the absolute number of inhabitants along the entire line must also be considered.

That number was calculated for German tram–train corridors. The results show that the number of reachable inhabitants lies between 19,000 and 47,000 persons but is mostly between 25,000 and 35,000.

Finally, consideration should be given to the standard gravity model indicating that the number of passengers increases toward 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 will people who are farther away from the center.

In summary, Table 2 shows that a population density of approximately 2,500 persons per kilometer is normally combined with a number of reachable inhabitants of 20,000 to 30,000 for a short corridor, while longer corridors with lower population densities (750 to 1,500 persons per kilometer) can serve areas with up to

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[a]	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

[a] >45 km.

50,000 reachable persons. These rules of thumb are 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 1 to 2 km, lightweight tram–train rolling stock can be used. These vehicles can accelerate quickly, and their energy consumption is lower than that of conventional trains. In general, tram–trains stop at all stations on the rail line and inner-city tram tracks. Having the tram–trains stop at all stations makes the use of true regional trains to provide express service on the same line possible. The subject of station spacing and stopping patterns for tram–train systems is an excellent topic for further research.

Technical Issues

System Change Area and Accessible Network

Since tram–train vehicles of Types A and B operate on both the city tram network and the standard-gage railway network, they need to be designed to operate with two different types of power supply, signaling systems, physical profiles, and so forth. Consequently, the tram–train rolling stock is generally more complex and expensive than are standard trams or comparable regional rail trains.

One aspect of operating with 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 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 the whole heavy rail network can be reached with just one interface. If several changeover areas are needed or several 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 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 adjacent to the city tram tracks and could be rebuilt easily into a through station for tram–trains (Figure 6).

Tram and Heavy Rail Track Technical Standards

The technical standards of the existing tram and heavy rail systems significantly influence 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, the cost–benefit ratio for a tram–train system is less advantageous.

Some key technical standards that help determine feasibility include accessibility for persons with disabilities, platform heights, the gap between rolling stock and platform, structure gages, and rail profiles. Tram–train vehicles must be able to operate on track and at stations of both the existing tram and heavy rail. If the networks are incompatible, the system needs new infrastructure. Examples include new station platforms or third rails in the case of rail gage differences. In both cases, the new infrastructure will increase capital costs and operating complexity. In Zwickau, where the inner-city track is 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 a 750-V tram system to 15-kV, 16.7-Hz alternating current or diesel. The difference is generally addressed by using dual mode tram–train vehicles. However, a region may also have several types of power used on the standard-gage rail lines. For example, in

(a) (b)

FIGURE 6 Karlsruhe Albtal railway station. (Photographs: L. Naegeli, 2010.)

Kassel, the tram–train system uses two 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 Saarbrücken (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 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 they determine the feasibility of a tram–train system. More complex systems reduce feasibility.

Quality of 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, with reduced travel time and increased comfort and passenger demand.

Therefore, an important part of analyzing the benefit of a tram–train system is evaluating the possibilities for improving the transfer between regional rail and city transit. Karlsruhe's experience is typical: the Albtal railway station and the main station were 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.

Institutional Complexity

In addition to being technically complex, tram–train systems are institutionally complex. The service operates in both cities and suburban areas—areas with different interests. On an operations level, the vehicles run on several types of track infrastructure with (generally) different owners and other operators. This means, for example, that train drivers must be trained on several networks. Thus, the system involves many actors, all with their own interests. Furthermore, a tram–train system can only be realized in coordination with cooperative city planning.

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

An important factor in the development of tram–train systems is 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. The 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 because of lack of funds or political support.

Strategic Planning

Thinking strategically is important in the planning of a tram–train system. For example, planners should compare tram–train systems with other solutions, including alternatives such as extensions of existing systems and improvement of transfer possibilities at the railway station serving regional trains. Both are good ways to achieve similar benefits at lower costs. Consideration should also be given to how the tram–train system fits into the long-range city and regional transport plan.

Strasbourg, France, is an excellent example. The city originally intended to extend its tram network in a first step and then connect it with the regional standard rail network in a second step. Since the project required an 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 a further extension to the city tram system.

CHECKLIST

The research goal was to develop a checklist for identifying optimal conditions for tram–train systems. The checklist was developed by using the factors discussed in the preceding sections. It provides a rough analysis tool for planners to use in evaluating 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 to 5 points). If a city seems suitable for introduction of a tram–train system on the basis of the checklist criteria, a more detailed analysis should be completed. The first aspect of this detailed analysis is capacity. In analyzing capacity, the possibility that the higher level of comfort and the shorter travel time provided by a tram–train system could significantly increase passenger volume should be taken into account.

DISCUSSION OF RESULTS

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. The mixed operation, and the many interfaces it creates, increases complexity and sometimes requires compromise solutions and changes in the existing networks. Although tram–train systems are designed to operate on existing infrastructure, they can be difficult and expensive to implement. Solutions found today in Karlsruhe or Kassel (inadequate accessibility for persons with disabilities) will not be accepted in future systems, which will increase complexity and costs.

Successfully introducing a tram–train system requires extraordinary cooperation between many stakeholders, including institutions, which requires time. Tram–train planning must be integrated into city and regional planning.

Under the right circumstances, tram–train systems can prove beneficial by 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. 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 (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 because of lack of capacity on the standard rail network. European experience shows that tram–trains can cause disruption in central pedestrian zones; therefore, 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

TABLE 3 Checklist for Possible Tram–Train Cities

Characteristics of 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 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 between villages)
12	Population density and reachable inhabitants
13	Possibility to connect a bigger city at the end of the deployment radius
Infrastructure and Technical Parameters	
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	
20	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 tram–train
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)

option for a city. Consideration of 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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