TRAM-TRAIN: CREATING NEW CONNECTIONS

Günter Koch, Head of Metro and Tram Design at DB Engineering & Consulting in Karlsruhe, assesses the strengths, weaknesses and ways forward for systems that combine rail and tramways.

An inherent aspect of rail transportation is that it cannot connect every point to every other point; this is overcome by connections within the system or across modes. For the passenger, this brings inconvenience and the risk of missed connections – changing modes also adds to journey times. In many large cities, tunnels were built for feeder traffic, but billion-dollar infrastructure is no model for small- and medium-sized cities which lack the patronage to justify it.

More than a century ago, ideas were advanced to take tramways out of the big cities. A different approach was taken in Karlsruhe, Germany. The metre-gauge Albtalbahn was acquired by the city in 1957 and converted to standard-gauge and 750V dc electrification, beginning in 1958. Since then trams and light rail trains have run between the urban network and the railway, while freight traffic is still hauled by diesel traction.

From 1979, the Hardtbahn was also integrated into the tram network; this line continues to operate as a railway and still carries occasional freight traffic. It is also electrified at 750V dc.

An ICE high-speed train and tram-train side by side at Frankfurt am Main station.
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Beginnings in Karlsruhe

Technically and operationally, it should be possible to run vehicles from the (urban) tramway onto (national) railway infrastructure and vice versa, negating the need to change on journeys between the city and the region.

A milestone was laid in Karlsruhe with the use of two-system tram-trains on the Deutsche Bundesbahn (DB) line to Bretten in 1992. For the first time, the municipal tramway was connected to a Federal line electrified at 15kV ac and using signalling technology commonly used by DB. The two-system tram-trains of the Albtal-Verkehrs-Gesellschaft (AVG) now ran directly from the region into the pedestrian zone of Karlsruhe.

The tram-train concept has since been adopted across both Germany and Europe. However, the frequently-cited 'Karlsruhe model' involves more than just the vehicles and their two-system technology. It would never have been successful without careful consideration of the schedule and fare structure, with the addition of closer stops, an adapted bus network and customer-focused marketing. There was also systematic expansion of rail transit in the city and region.

Law and terminology

German law makes clear distinctions between railways and tramways. The diagram to the right (Figure 1) shows how the tram-train concept bridges these systems. The Railway Construction and Operating Regulations (EBO) apply to mainline railways, both the national railway infrastructure (e.g. DB Netz) and the private, non-federally-owned standard-gauge railway (NE). 'Tramways' include subways and elevated railways under the regulation of the Ordinance on the Construction and Operation of Tramways (BOStrab).

Table 1 (right) proposes some definitions; in particular, the delineation between tram-train and two-system tram-train.

In Germany, the term two-system tram-train is used for networks where trams travel over (national) rail infrastructure and operate under an overhead line voltage of 15kV ac. Internationally, the term tram-train is generally used when there is a transition

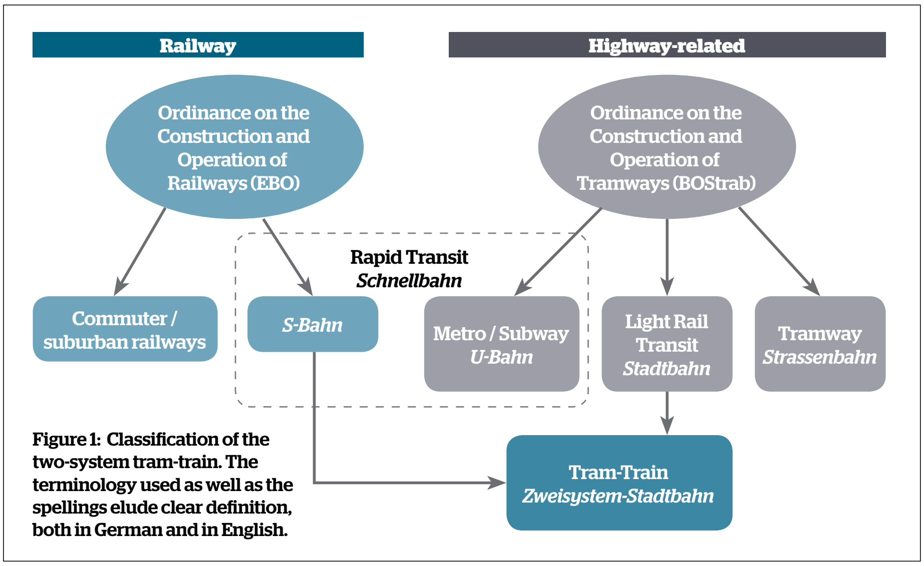


Figure 1: Classification of the two-system tram-train. The terminology used as well as the spellings elude clear definition, both in German and in English.

TABLE 1: COMMON DEFINITIONS AND TERMINOLOGY

Terminology (German)	Terminology (English)	Criteria	Description	Remarks
Tram-train (TT) *Regional-Stadtbahn*	Tram-train	Change of operating regulations	Change-free connection between urban and regional rail; linking trams and railways	e.g. Nordhausen, Chemnitz - Stollberg
Zweisystem-Stadtbahn (ZS) (*Zweisystembahn*)		Change of operating regulations and power supply	The two-system tram-train is a subset of the tram-train	e.g. Chemnitz, Karlsruhe, Kassel, Saarbrücken,
Tram (*Tram/Trambahn*)	Tramway / Streetcar / Trolley	Operation with other road traffic	Railways using the traffic area of public roads, or having a separate right-of-way, also elevated and underground railways	
Stadtbahn	Light rail	Synonymous with a modern, attractive and cost-effective urban - and also regional - rail system.	Operation with other road traffic or also as an independent railway	No generally valid definition
Train-tram	Train-tram	Mainline rail vehicles on tramway infrastructure		e.g. Zwickau
Überlandstraßenbahn	Interurban	Tramway serving transportation links in the wider region		Today, they are mostly operated as light rail systems or metros (e.g. Köln, Düsseldorf);
Eisenbahn	Railway	Rail system according to national legislation		Mainline railways and narrow-gauge railways are a subset
Vollbahn	Standard gauge (railway) / mainline	Railway with standard gauge		Also broad gauge, including Finland, Ireland, Iberian Peninsula as well as Russia and Baltic countries
Nationale Eisenbahn	National railway	Interoperable railway according to EU directives		Former state railways, e.g. Deutsche Bahn

"The tram-train concept would never have been successful without close consideration of the schedule and fare structure, but also closer stops, an adapted bus network and customer-focused marketing."

TABLE 2: COMPARABLE RAIL SYSTEM PARAMETERS

Technical data	Railways (1)	Light rail transit / tramway (2)
Higher-level dependencies	Trans-European Networks (TEN)	Participation in road traffic
Minimum curve radii	from 150 m up to 300 m for new lines r ≥ 300 m for main lines r ≥ 180 m for branch lines	r ≥ 25 m (23m)
Permissible gradients	≤ 35 ‰ main lines ≤ 2.5 ‰ tracks through passenger platforms	Usually 40-60‰ (85-105‰ implemented)
Vehicle width	Up to approx. 3m (e.g. ICE 1 / Class 401)	≤ 2.65m for street-running railways
Train lengths	≤ 400m	≤ 75m for street-running railways
Axle load	18 to 22.5t	≤ 11.5t (3)
Power supply	Usually 15kV 16.7Hz or 25kV 50Hz ac	Usually 750V dc

Notes:
1. The values given refer to the TSI (Technical Specification for Interoperability) and vary in different countries.
2. The values given generally refer to street-running railways.
3. The reference vehicle is *ET2010* Karlsruhe, otherwise no specifications; comparable design loads to road traffic.

between tram and (national) rail, irrespective of power supply. Two-system tram-trains are therefore a subset of tram-trains.

In Germany, as in Austria and Switzerland, an *S-Bahn* is an urban and regional rail service with a cyclic schedule. In train-tram systems, rail vehicles run on tram tracks, such as in Zwickau. Interurban tramways still exist, but they do not work under differing operating regulations or power supply.

Making the transition

Regional and urban rail systems should be adapted to local requirements in terms of construction and operation in order to achieve both transportation and economic objectives. A major advantage of light rail networks over railways in this respect is the application of design parameters which are better adapted for urban environments, as well as the possibility of street-running. Such comparable parameters are outlined in table 2 (above right).

For a tram-train or two-system tram-train with a transition to the national rail network, the main issues are as follows:

- Different legal bases, in particular the construction and operating regulations
- Differing power systems, taking into account contact wire heights and layouts
- Signalling, radio and train protection systems
- Axle-guidance (the interaction between wheel and rail, taking into account the negotiability of grooved tram rails in streets or points and crossovers on railways)
- Mode of operations – driving with train protection (EBO) or line-of-sight (BOStrab) in Germany
- Individual personnel training regimes
- Different regulatory agencies, which, for example in Germany, are responsible for:
  - Federal railways: Federal Railway Authority (EBA)
  - Non-federally owned railways (NE): State Railway Supervision (LEA)
  - Tramways (light rail): Technical Supervision Railways (TAB)

There is no overarching regulation as every system change has its own peculiarities.

A critical element is the transition from the 15kV or 25kV ac mainline to 750V dc and vice versa; other rail systems may have different voltages or frequencies. As the transition is crossed with momentum, without manual intervention, the speed must be sufficient so the vehicle does not come to a standstill; there should also be no circumstances which make braking necessary in this section, such as platforms, grade crossings or signals. ➤

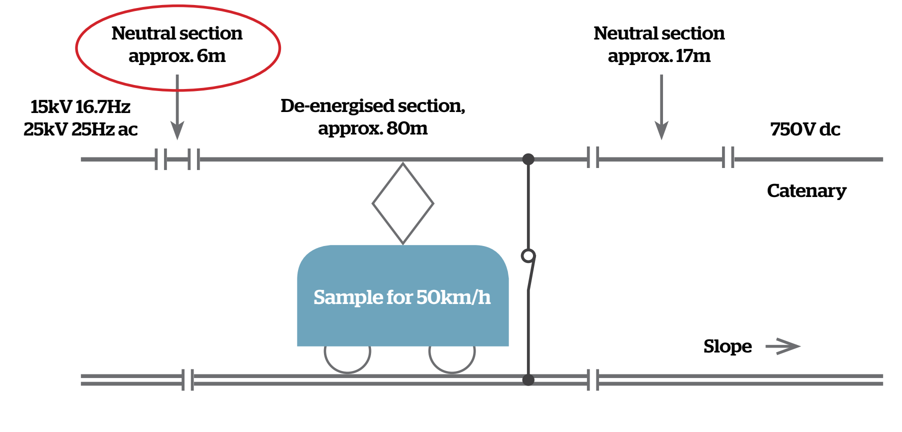


Figure 2: A conceptual transition between power supply systems.

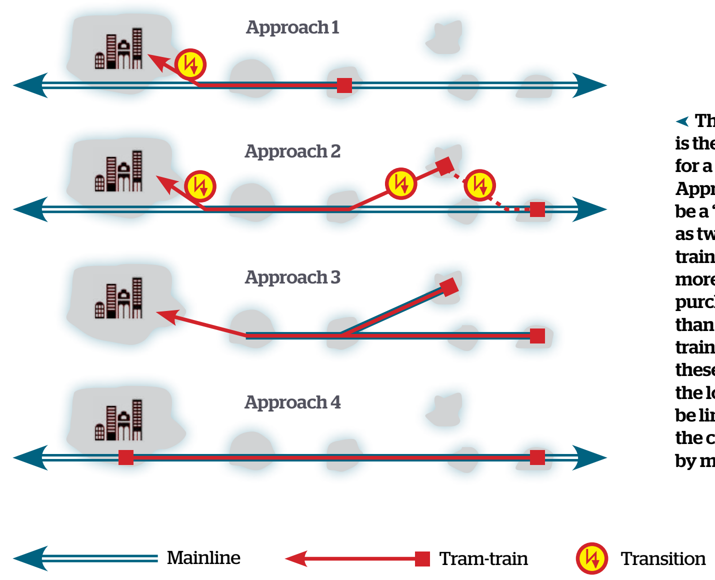
A conceptual transition design is shown in Figure 2 above. For reference, to the right we see such a transition in Karlsruhe, with the neutral section highlighted with a red circle.

In Chemnitz, Kassel and Nordhausen, bi-mode vehicles are employed – an internal combustion engine with an electric generator produces energy for the electric drive. Traction power generation from a hydrogen fuel cell or a battery for energy storage is also conceivable.

Connecting people and places

The primary goal must be bringing the rail service to the people. Traditionally, railways have been based around other criteria – primarily station-to-station, rather than door-to-door, journey times. This is fine for long-distance travel, but not for regional trips as for decades many settlements have been developing away from railways. Light rail, however, has always been based around how people can best reach stops on foot or by bicycle.

▲ The Karlsruhe – Grötzingen power supply transition, as seen looking toward the 750V dc network.



◄ The first approach is the typical case for a tram-train. Approach 4 cannot be a 'standard' model as two-system tram-trains are generally more expensive to purchase and operate than conventional trains.[1] In Karlsruhe, these services will, in the long-term, either be linked through to the city or replaced by mainline trains.

Light rail systems therefore differ from railways in that their design parameters can follow urban development patterns more easily (to serve residential, commercial or leisure locations) to determine where a route and its stops should be located. The decisive factor is that timetable speeds are optimised and susceptibility to faults is minimised.

There are many approaches when designing a tram-train network:

Approach 1: Light rail is developed from a tramway and extended to the region via railways.

Approach 2: Trains branch off regional railway lines and continue as light rail into built-up areas. Here, a special inner-city line is added to allow the trains enter the town. A combination with Approach 1 is possible. Figure 3 (below left) shows how this was achieved in Kaufungen near Kassel.

Approach 3: Regional railways are linked to local tramways. The railway will be brought into line with the requirements of the tramway wherever possible.

Approach 4: Light rail vehicles are used exclusively on railway lines, replacing mainline vehicles.

▲ Figure 3: The light rail line (green) leaves the mainline (yellow) in Kaufungen near Kassel.

Platform heights and horizontal gaps

Light rail vehicles and metro trains are largely proprietary systems and therefore have neither uniform platform heights nor standardised platform gaps.

The requirement for barrier-free access throughout makes it necessary for the light rail system to match the rail network with which it interacts; the complex issue of platform heights is not made easier by two-system operation.

Historically, platform heights on German railways have been 380mm or less. To take account of available infrastructure in the 1990s, these heights were adopted for the two-system tram-trains in Saarbrücken and

An example of the neat integration of a 550mm-high platform into an urban environment in Heilbronn.

Combined platforms in Karlsruhe: A 550mm platform is used for light rail services (left) and a 340mm platform for city trams (right).

A combined platform at Karlsruhe Durlach station with a height of 760mm for the Rhein-Neckar suburban railway (left) and 550mm for light rail (right).

"The Karlsruhe solution, with 550mm platform heights, offers a good compromise as large parts of the mainline network are compatible with local mass transit."

Kassel. Meanwhile, in the tramway sector, low-floor vehicles had been developed with a focus on barrier-free access.

Also in the 1990s, AVG specified a 550mm platform height for its future network of two-system tram-trains as well as a second-generation of vehicles with medium floor heights and entrances optimised for this platform height. Some stops on the Karlsruhe Transport Authority (VBK) municipal tram network now also have barrier-free access to the medium-floor vehicles. Combined platforms compensate for differences when vehicles with different door sill heights are used. This is achieved either by raising (tramway, top right) or lowering a section of the platform (railway, top centre). The goal is to provide barrier-free access through at least two doors.

The European Union's Technical Specifications for Interoperability (TSI) define a standard platform height of 550mm. This has already been implemented network-wide in Austria and Switzerland, and to some extent in France. Such platforms can be integrated into an urban environment, as seen in Heilbronn (top left).

BOStrab limits the width for vehicles participating in road traffic to 2.65m. For railways, the width is defined by the standard clearance according to EBO that must be maintained by the vehicles. The distance between the edge of the vehicle entrance and the platform is termed the horizontal gap. An overview of platform heights and horizontal gaps is shown in Figure 4 (above right).

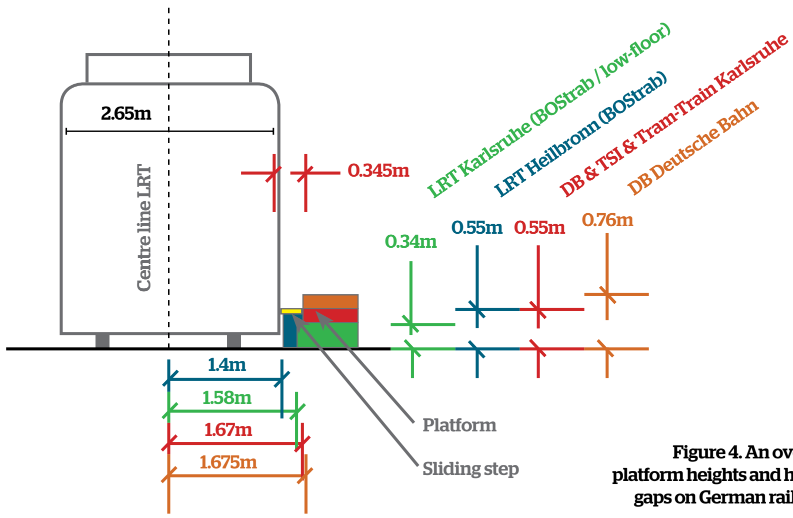


Figure 4. An overview of platform heights and horizontal gaps on German rail systems.

This complexity gives an idea of the main challenges when designing platform systems:

- Barrier-free accessibility for boarding and alighting (step-free at all platforms)
- Minimisation of the vehicle-platform gap (the approx. 350mm horizontal gap which has to be bridged)
- Urban integration (minimisation of platform height – the lower the better)
- Compatibility with railways (taking into account requirements for long-distance and other regional services)
- Compatibility with the inner-city tramway (use of shared platforms)
- The need to overcome a height difference of one step up or down.

This in turn results in various solutions:

a) Equipping vehicles with variable sliding or moveable steps. Almost all tram-train systems have solutions for overcoming height differences and bridging the gap between vehicle and platform.

b) Platform sections with different heights (combined platforms); as described above, this solution is convenient whenever long-term standardisation of boarding conditions is not expected.

c) Different door sill heights in the vehicle to provide a high level of operational flexibility: in Chemnitz, this solution was chosen with different door sill heights at different platforms (see right).

The Karlsruhe solution, with platform heights of 550mm, offers a good compromise as large parts of the mainline rail network are compatible with local mass transit.

Vehicle considerations

The TSI contain the following definition: "A tram–train is a vehicle designed for combined use on both a light rail infrastructure and a heavy rail infrastructure".[2] However, these vehicles are explicitly excluded from the application of the TSI in the relevant Annex 2.3.1.

Tram-train vehicles must be certified for both railway and tramway use and comply

Concept of low/medium-floor access points (front without and middle with moveable step) in Chemnitz. ➤

with the relevant guidelines. According to BOStrab, trains used on the street must not be any longer than 75m; most LRVs have a length of 37.5m, so a double consist is within the maximum permissible length.

Limiting axle loads to 11.5t is based on the requirements of the road infrastructure, including the substructure. Transformers, crashworthiness standards and many other details make two-system tram-trains heavier than ordinary light rail vehicles; individual requirements such as onboard toilets can also add to the overall weight. The general design is based around the construction of light rail vehicles, and the bogies therefore enable speeds of up to 100km/h (62mph).

One would expect the lighter construction of an LRV to make specific procurement costs per passenger space to be lower than for a mainline train. However, the technical requirements are significantly higher, for example the need to negotiate curves with 25m radii as well as to participate in road traffic. This and the axle-weight restriction result in a costly design. Moreover, components such as driver's cabs, transformers or pantographs are distributed over a shorter vehicle length so a 37m tram-train has proportionately more equipment than a classic suburban train.

A tender for a new generation of tram-train vehicles led by the VDV association of public transport undertakings (Verband Deutscher Verkehrsunternehmen) was launched in 2020. In January 2022, a base order for 246 vehicles was placed with Stadler (with options for up to 504) to be distributed between the systems in Karlsruhe, the Neckar-Alb region (Reutlingen/Tübingen), Salzburg, Schiene Oberösterreich (Linz, Austria) and Saarbrücken in various designs. Their use is planned from 2024, for platform heights of 380mm and 550mm.[3]

▲ **ABOVE: A *RegioShuttle* railcar runs on the city rail network under BOStrab rules in Zwickau.** Steffen Schranil

▲ **ABOVE: A standard-gauge *Citylink* from Chemnitz (left) visits the metre-gauge Zwickau tramway in 2021.** Steffen Schranil

Operational aspects

Transportation benefits can be achieved by employing comparatively short trains travelling at tight intervals. This is common for light rail vehicles, but cannot so easily be applied to mainline railways.

The nature of a light rail system, compared with a suburban railway, is to achieve the most complete coverage possible within a corridor. This limits distances between urban stops to around 500m-700m, and around 1km (0.6 miles) in rural areas. Buses are therefore only seen as feeders from outside the connected corridor. This is also essential for the economic efficiency of a tram-train service.

On congested rail networks, integrating tram-train lines is a further challenge. In the inner city this mainly affects motor traffic, which causes disruptions and obstructions for the railway – many interventions in operations that can hardly be planned for. Light rail can also get in its own way if the network has too high a load factor; line capacity is also a major source of disruption on many rail networks. Added to this is the often very high level of delays found on inter-regional traffic.

"Lower maximum speeds and lower acceleration values can make it difficult for LRVs to 'swim along' on mixed traffic routes."

Operational quality as well as line capacity are also negatively affected by two key disadvantages of light rail: lower maximum speed and lower acceleration values at higher speeds. This can make it difficult to 'swim along' on mixed traffic routes – or requires appropriate operational or infrastructure measures.

The consequence is that two-system traffic should be limited on routes with a high level of mixed running, however this depends on the range of speed levels, journey times, train numbers or types. If two-system tram-trains have to be overtaken by other trains, this increases journey times for the former.

Case studies from German cities

Today, Karlsruhe operates a 660km (410-mile) network, including that in Heilbronn, with 160 two-system tram-trains. The city's 'Combined Solution' began service at the end of 2021, the centrepiece of which is the T-shaped tunnel under Kaiserstrasse with its branch south to the main railway station. Together with the new tramline in Kriegsstrasse, this will create additional capacity. Most importantly, better reliability is expected, especially for tram-trains, as the underground network will reduce disruption from surface traffic.

In Chemnitz, as in Kassel, as mentioned earlier, some of the two-system tram-trains are diesel-electric hybrids and the city's main station was rebuilt for tram and light rail use.

Zwickau has the only operational train-tram system. Standard-gauge diesel railcars use a four-rail track to reach the city centre together with metre-gauge trams. A short visit by a *Citylink* from Chemnitz last spring proves the flexibility of two-system technology.

A planned two-system project is the Regionaltangente West (RTW) in and around Frankfurt am Main. Construction of around 23km (14 miles) of new lines under BOStrab is planned together with the use of almost the same length of DB Netz tracks, including the regional station at Frankfurt Airport (Figure 5, right). The vehicles will have a door sill height of around 800mm, to be able to stop at platforms with a height of 760mm or 960mm.

The Neckar-Alb regional light rail system is already under construction, intended to revitalise rail transit in the districts of Reutlingen, Tübingen and Zollernalb. Under this project, existing rail lines will be electrified and additional stations opened; new light rail lines are also being built and some rail lines reactivated under BOStrab. This will result in a 205km (127-mile) network. Light rail routes which do not use BOStrab lines will be primarily operated by mainline vehicles. Commissioning of a first section is planned for the end of 2022. However, rejection of a planned urban route in Tübingen by the city council is a setback.

Austria's Salzburger Lokalbahn operates its railway with light rail vehicles under 1000V dc, with freight traffic crossing directly onto the Österreichische Bundesbahnen (ÖBB) network. There is a tunnel section with a stop under the forecourt of the main station, and an extension under the city with a through-connection to the south is planned. Salzburg is also part of the VDV Tram-Train procurement.

In Aachen, too, studies are underway which could ultimately lead to a two-system tram-train (under the 'Regio-Tram Basis' scenario).[4]

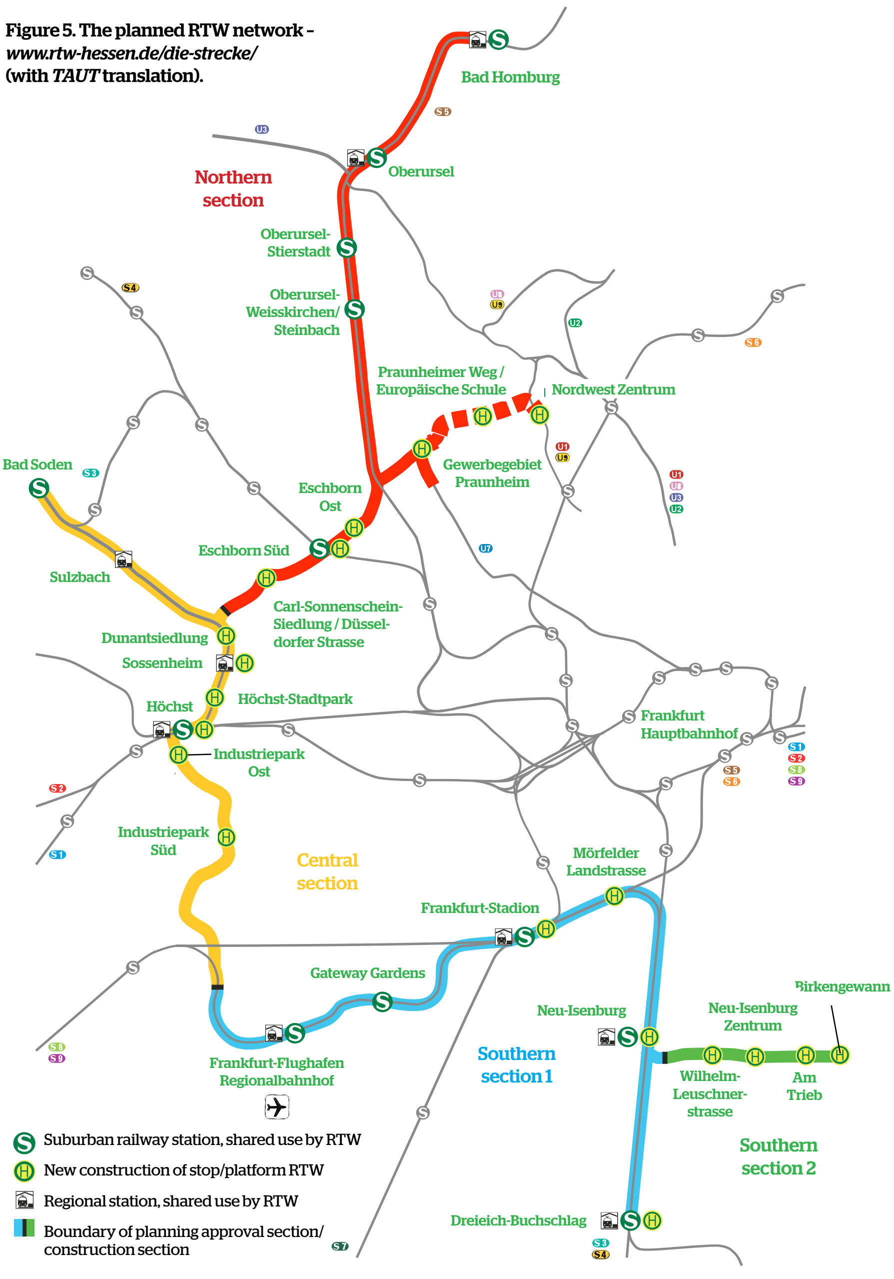
A different approach has been taken in the Netherlands. RandstadRail is operated as a hybrid, with low-floor LRVs toward Den Haag (with a transition to the tramway) as well as high-floor metro trains and a connection toward Rotterdam and its metro network. Some stations are served by both systems.

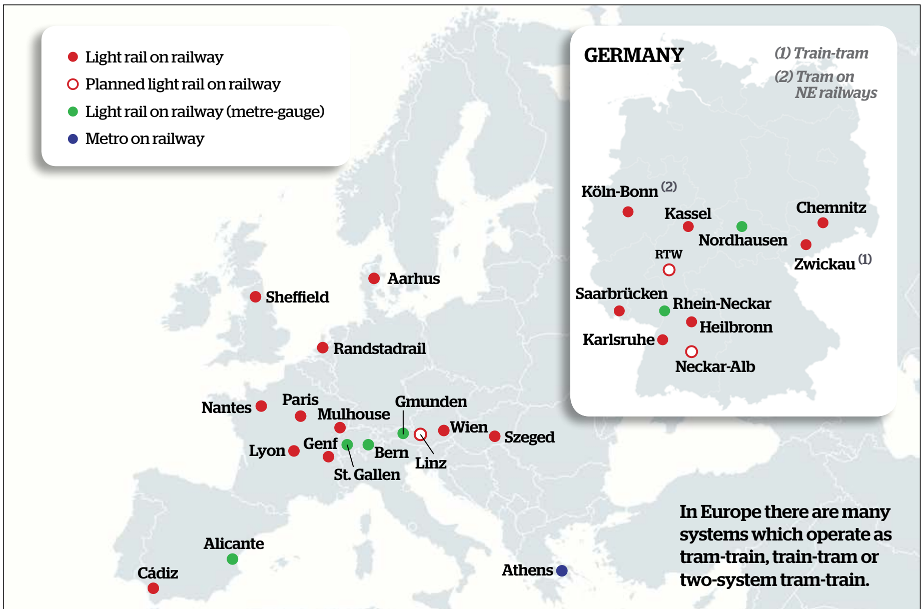
Looking to the future

To truly enable a mobility revolution it is necessary to overcome the divide between light rail and railway, and openly seek technical and legal solutions which provide the best options. It must not be a question of vested interests, but of the best, most economical and environmentally-friendly solutions.

There are new opportunities for trams, light rail vehicles and tram-trains, not only in metropolitan areas and conurbations, but also smaller agglomerations. The people with responsibility and citizens just have to rethink mobility – and begin with the conversion and expansion of public transportation as an alternative to the private car. TAUT

Figure 5. The planned RTW network – *www.rtw-hessen.de/die-strecke/* (with *TAUT* translation).





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