Tram-train: when is it a suitable mode?

Development of a model to determine applicability of tram-train

January 2019

Sander Willer

Mott MacDonald
Amsterdamseweg 15
6814 CM Arnhem
PO Box 441
6800 AK Arnhem
The Netherlands

T +31 (0)26 3577 111
mottmac.nl

Tram-train: when is it a suitable mode?

Development of a model to determine applicability of tram-train

January 2019

Registered in Arnhem, The Netherlands
no. 30199525.

Sander Willer

Tram-train: When is it a suitable mode?

Development of a model to determine applicability of tram-train

by

S.L. Willer

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday January 24, 2019.

Student number:	4151836	
Project duration:	March 19, 2018 – January 24, 2019	
Thesis committee:	Prof. dr. R.M.P. Goverde,	TU Delft, Chair
	Dr. ir. N. van Oord,	TU Delft
	Dr. A.A. Núñez Vicencio,	TU Delft
	B. Godziejewski, MSc, MBA,	Mott MacDonald

An electronic version of this thesis is available at https://repository.tudelft.nl

Disclaimer

Information class: Standard

Cover image: A Kassel RegioTram next to an InterCityExpress, a German high-speed train. Humme Station. Kasseler Verkehrs-Gesellschaft, 2016. https://www.kvg.de/presse/news/aenderung-fuer-einzelne-zuege-der-linie-rt1-1/

Preface

With this thesis, I conclude the Master of Civil Engineering, specialisation Transport and Planning, at the Delft University of Technology. I have spent the past nine months pondering about trams, trains and especially one of the modes in between: tram-train. This thesis is about the research I have conducted at Mott MacDonald, studying the applicability of tram-train. I am very grateful for having received this opportunity, which also enabled me to speak to various experts from the sector and visit the birthplace of tram-train; Karlsruhe.

I would like to thank Niels van Oort, Bogdan Godziejewski and Ricks Schalk for regularly keeping up with my progress and being actively involved in my work. Moreover, I would like to express my gratitude towards Professor Rob Goverde and Alfredo Núñez Vicencio for their input during the formal meetings.

Furthermore, I would like to thank all my colleagues for their interest in my work, enthusiastic discussions, and I look forward to collaborating with them in the near future. Many thanks as well to the external experts for their time, passionate stories and good advice.

Lastly, I would like to thank my friends for the welcome distraction from this work, and especially Arthur for his help on the visual aspects of this document and the fruitful discussions at the university. And naturally, I owe many thanks to my parents for their continuous motivation and support during the past years.

Enjoy the read!

Sander Willer,
Delft, January 2019

Executive summary

In a world where the demand for mobility around cities is increasing, providing efficient public transport is becoming more and more important. However, many countries including The Netherlands are experiencing challenges with main train stations being used up to their capacity, with little to no room for expansions. The concept of tram-train, originating in Karlsruhe, Germany in 1992, connects regional train lines to urban tram networks. Passengers can travel from regional villages directly into the centre of the main city, without using scarce platform space in the station. The first lines proved to be very successful, and the network around Karlsruhe has grown considerably, with similar systems having evolved in other cities. In the Netherlands, the RandstadRail is a very successful implementation of tram-train. However, it is different from the Karlsruhe concept as it combines a metro-train and tram-train system and is an example of how most implementations of tram-train systems are the result of locally engineered solutions.

Available literature about tram-train is mostly limited to describing examples from practice, although some literature on the applicability of tram-train is available. In these papers, checklists to aid in implementation of tram-train are presented. However, those checklists have a very wide scope and leave much room for interpretation. A generalised, but more quantitative approach to implementing tram-train would aid in the understanding of the suitability of tram-train and ease future application of the concept. In this thesis, it is aimed to develop such a generalised approach by answering the main research question:

> *How can applicability of tram-train in an urban region be evaluated using a generalised approach, based on both public transport and city characteristics?*

Improvement objectives for urban public transport

Public transport can be regarded from the perspective of three main stakeholders; the operators, the government and the passengers. Operators strive for profit and aim at concentrating ridership at a limited number of trips, while governments aim at providing the most cost-efficient public transport. Typically, providing public transport is more expensive than its direct benefits cover. However, the overall benefits can be increased by also considering societal benefits. For passengers, public transport should be more attractive than other modes. The attractiveness of a service depends on several criteria, with travel time being one of the most important. The distinction in time-valuation of trip parts is captured in experienced travel time, and it is observed that transfers pose a large penalty to experienced travel time.

Considering the perspectives of the three stakeholders and to meet their objectives, five measures for improving public transport in urban regions were defined:

- Increase line capacity
- Decrease (experienced) travel time
- Increase network coverage
- Improve sustainability
- Improve passenger experience

Tram-train

Tram-train was developed in the German city of Karlsruhe. A line was created which was operated as a tram within the city centre and as a train on the regional heavy rail line. The heavy rail tracks were shared with ‘real’ trains. This concept was extended, and other forms of tram-train were

developed; both with and without track sharing on the heavy rail and/or tram section. This distinction results in four classes (A - D), which are illustrated in Figure 0-1.

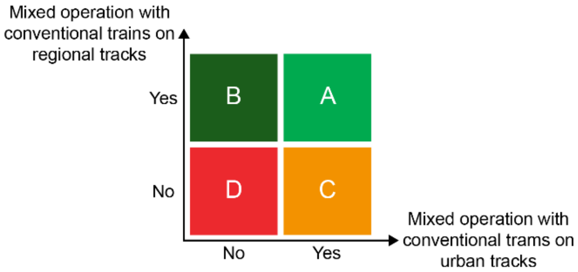


Figure 0-1: Classification of tram-train. Adapted from Naegeli et al. (2012).

To gain insight in the state-of-the-art of tram-train, several existing European systems (shown in Table 0-1) were analysed on unique features. For instance, in the Karlsruhe network, a notable feature is that vehicles have a floor height of 55 cm. However, this results in limited accessibility on the urban tram network. In Chemnitz and Cádiz, the accessibility issue was overcome by constructing vehicles with two floor heights. Kassel was the first city to operate diesel-powered light rail vehicles, as one of the regional lines could not be electrified.

Table 0-1: Reference systems.

Germany	France	Netherlands	United Kingdom	Spain
Karlsruhe (network)	Mulhouse (single line)	Hoekse Lijn (single line)	Sheffield (single line)	Cádiz (single line)
Kassel (network)	Nantes (network)	RijnGouweLijn (single line)*	Cardiff (single line)	
Chemnitz (network)	Paris (single line)	RandstadRail (network)		
Nordhausen (single line)		Groningen (network)*		

Note: * System was proposed but not implemented.

The reference systems were also analysed on population figures and operational parameters such as line length, stop spacing and average speed. The analysis resulted in typical operational parameters of tram-train, which were compared to ‘traditional’ modes, such as urban tram, regional tram and regional trains (Table 0-2). It was found that overall, tram-train lines have similar characteristics as regional trams. When the tram and train sections are analysed separately, the respective parts of tram-train lines are relatively short. Considering average speed, tram-trains are significantly slower than regional trains. On the other hand, urban tram-train sections have a slightly higher average speed than typical tram networks. Tram-train vehicles have similar dimensions as trams but reach higher top speeds. On regional lines, double traction is often used to increase the train capacity.

Table 0-2: Comparison of operational parameters.

Parameter	Regional train	Tram-train; train section	Urban tram	Tram-train; tram section	Regional tram	Tram-train; full line
Mean line length	> 20 km	23.6 km	5 – 20 km	6.7 km	10 – 40 km	32.6 km
Mean stop spacing	2 – 5 km	2.4 km	200 – 600 m	450 m	0.4 – 2 km	1.7 km
Mean speed	> 60 km/h	45 km/h	15 km/h	19 km/h	30 - 45 km/h	37 km/h
Max. speed	> 100 km/h	100 km/h	< 70 km/h	< 70 km/h	< 80 km/h	100 km/h

Tram-train can be used in a regional public transport in three ways. As main mode, in which tram-train is the only rail mode serving regional settlements; as secondary mode, in which regional trains serve the large towns, and tram-train serves additional stops and smaller villages; or as feeder mode, in which tram-train is used to provide access to higher-level rail modes. This mode is most useful as tangential lines in large cities.

The main advantage of tram-train is the elimination of a transfer between regional and urban public transport. Moreover, tram-trains allow shorter stop spacing compared to regional trains. Tram-train can be used to extend existing rail networks into a city without complying with limiting heavy rail legislation and relieve platform capacity at large nodes. Generally, relatively few investments in infrastructure are required, as tram-train uses existing infrastructure. However, the vehicles are more expensive than regular trams. One of the largest threats to tram-train is the required cooperation between many stakeholders; local and regional governments, regulatory bodies, a transport authority, an infrastructure manager, and local, regional and national operators. Ideally, the transport authority is the only involved political stakeholder, which can ease the political decision-making process.

An initial selection of relevant criteria regarding the applicability of tram-train was made by studying literature on tram-train. This selection was extended by including knowledge of ‘traditional’ modes and interviews with experts from the field. Within the scope of this thesis, four categories, which cover several criteria have been defined:

I. *Population of city and regional corridor.*
Tram-train was found to be most suitable in cities with a population between 100 and 400 thousand inhabitants, although no clear upper boundary could be defined. The absolute population of a regional corridor is not directly related to the possibility of tram-train but should be regarded relative to the corridor length. Lower and upper boundaries were estimated to be 500 and 4500 inhabitants per line-km. Moreover, for class A and B systems, the potential capacity can be constrained by other usage of heavy rail tracks. As a result, the serviceable population per line-km decreases for longer lines. A linear frontier was estimated to quantify this decrease. The resulting thresholds are outlined in Figure 0-2. The actual residential density around stops further specifies the suitability of tram-train.

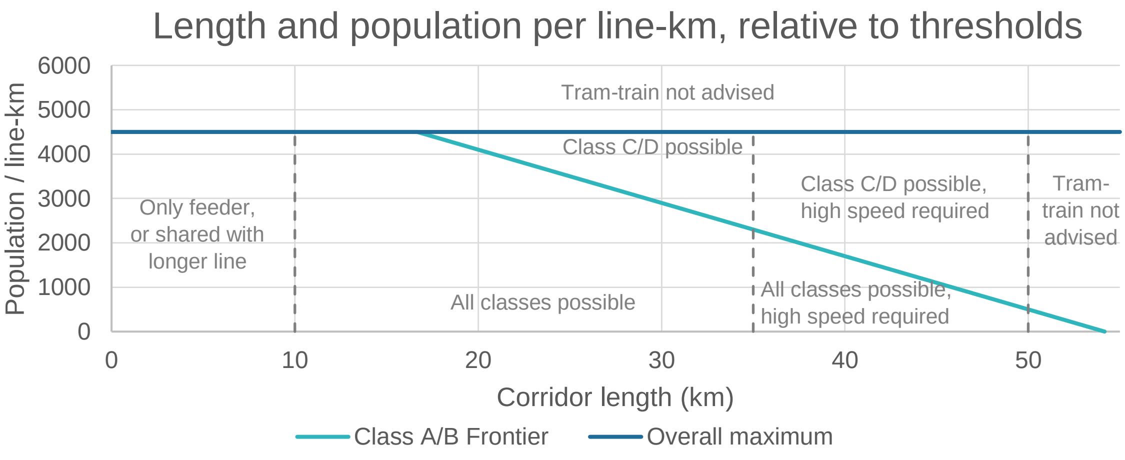


Figure 0-2: Population per line-km threshold relative to line length.

II. *The relation between the urban region and the main city*.
Tram-train can be successful if there is a strong social and economic focus from the region towards the city, and when attraction centres are not located adjacent to railway stations. Direct services towards large educational institutions provide additional transport demand, as students are typically reliant on public transport.

III. *The existing rail networks.*
A proposed tram-train should not become a direct competitor to existing high-quality rail modes into the city centre. There should be heavy rail infrastructure present, but tram infrastructure is not required. However, implementation will be cheaper when only a short connection needs to be built. The possibility of integration with the existing tram network depends on the vehicle dimensions and the level of service. If the desired tram-train vehicles are wider and longer than the existing fleet, this might require extensive modifications of the tram network. Secondly, especially class A and B tram-trains require a high punctuality because of their integration within a heavy rail timetable. Long sections of street alignment, pedestrian area and gauntlet track, and short headways make a tram network less suitable for tram-train lines. The possibility of integration with the heavy rail network mainly depends on the track layout and the capacity consumption, with the design speed of the tram-train vehicles influencing the necessary capacity.

IV. *Access and egress modes.*
Cycling can be supportive to tram-train in cities where the bike is not a direct competitor. Moreover, tram-train can be more successful if coordinated with regional public transport in small hubs and when park & ride can be offered in the scheme.

The criteria on the relation between the urban region and main city (category II) are the most important when defining the suitability of tram-train. Those criteria are specifically related to the basic concept of tram-train and define the transport demand for such services.

Evaluating the applicability of tram-train

A three-step top-down approach to determining the possibility and suitability of tram-train for an urbanised region was developed, which is outlined in Figure 0-3. In each step, the solution space for tram-train is narrowed down by a more detailed analysis.

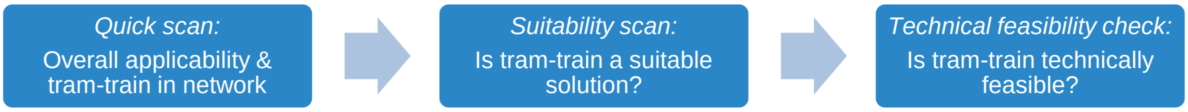


Figure 0-3: Outline of model steps.

The first step, the quick scan, assesses the possible application of tram-train in an urban region. A quantitative analysis of the population, infrastructure and heavy rail usage is performed by following decision schemes. A proposed corridor is evaluated against the threshold values on population and line length (Figure 0-2), predefined scenarios on infrastructure and rough capacity estimations for heavy rail usage. In cases where the quick scan indicates that there is no possible implementation of tram-train, one does not need to perform the second and third step but should focus on studying a different mode.

In the second step, the suitability scan, it is analysed whether the city and rail transport network characteristics provide enough solution space for application of tram-train, by means of a multi-criteria analysis. The result is a generic evaluation of tram-train being not realistic, not very suitable, suitable or very suitable for the analysed urban region. The weighted-sum method is used to determine the suitability score of a proposed corridor. The score is based on compliance with the criteria which were not dealt with in the quick scan. Expert judgement was used to determine the weight for the various criteria. Outcome score ranges were defined by evaluating the reference systems. To overcome minor inconsistencies in input, fuzzy logic was used with which transition zones between the ranges were defined. If none of the analysed corridors yield a suitable result, it is not necessary to continue to the third step of the analysis.

While verifying the quick and suitability scan with existing systems, it was found that they are most applicable for regions with a single main city and less populated surrounding. For urban regions with large corridor populations (e.g. when other large cities are served), the quick scan is considerably less usable due to the population thresholds. For regions without a clear main city, the required inputs for the suitability scan can be difficult to determine.

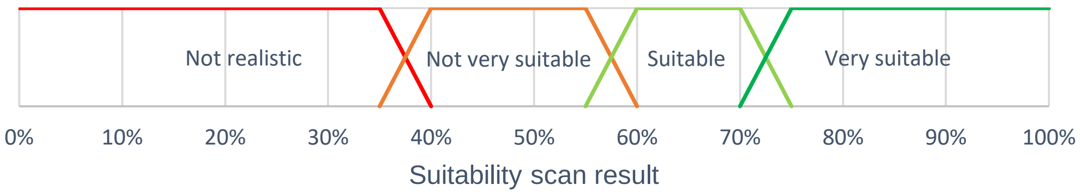


Figure 0-4: Suitability scan outcome ranges.

Lastly, an indication of relevant interfaces between the tram and train system is provided, which can be used to study the technical feasibility of tram-train. The relevant interfaces follow from the applicable tram-train class, which was determined by the quick scan. To find all interfaces, a framework for systematic identification of the interfaces between tram and train systems was developed. Lessons learned and literature were studied to create a library of solutions and caution points on issues at the interfaces. The indicated relevant interfaces and library should be used to locally optimise the technical integration of tram-train. Generally, there are no technical issues which are unsolvable, but some interface issues might not be solvable locally due to limitations such as available space. In these cases, tram-train is technically unfeasible.

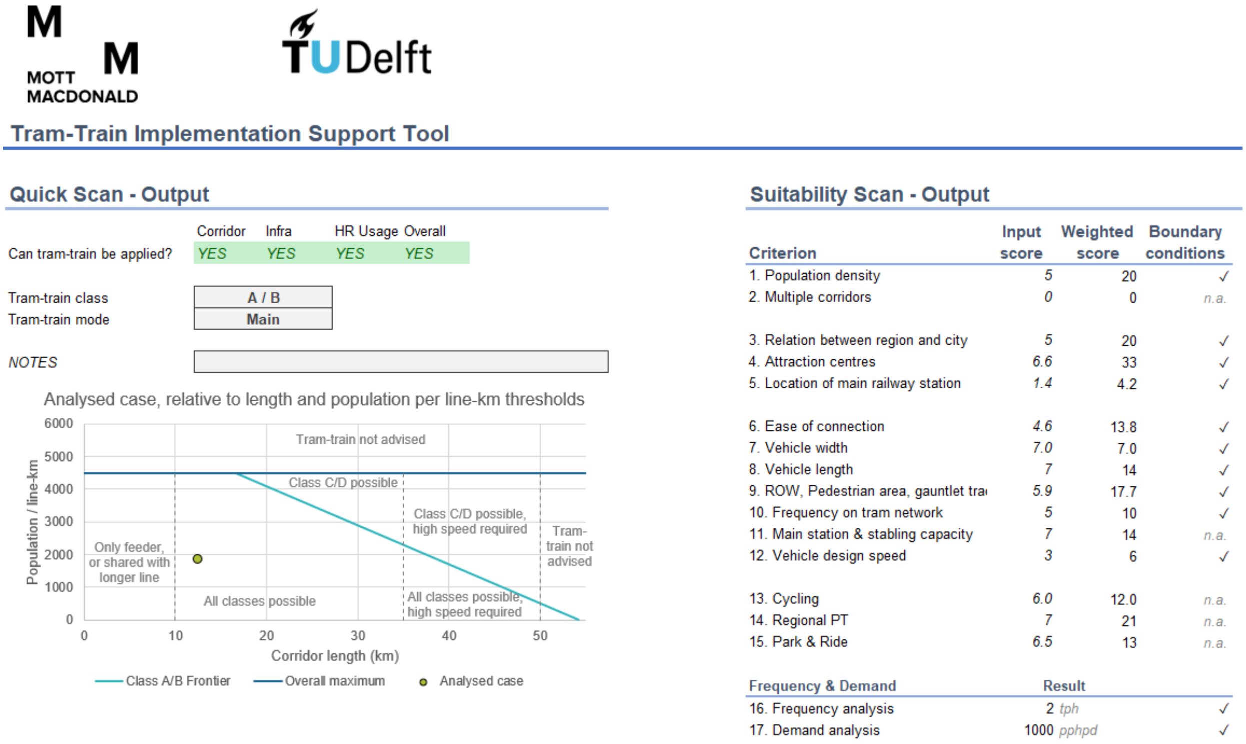
Tram-Train Implementation Support Tool

The Tram-Train Implementation Support Tool (T-TIST) was designed to make the developed models easy and comprehensible to work with. The T-TIST was created in Microsoft Excel and requires easily obtainable inputs. In three steps, the tool performs the quick scan and suitability scan, and indicates the relevant technical interfaces. In the tool, an interactive environment is created where users can immediately see the effect of altered inputs. A manual is provided with the tool, to support users in choosing correct input categories. Figure 0-5 shows a screenshot of the T-TIST. The T-TIST can be improved in the future by enabling it to compare various corridors and deal with lines which consist of sections of different tram-train classes. Moreover, including a travel time analysis function would support the advice given by the T-TIST.

Case studies

The developed T-TIST was reviewed by performing two case studies. The cases were used to reflect on the usability and reliability of the tool. The first case was the corridor from Baarn, via Soest, Bilthoven and entering the city via a lightly used railway. There, it is connected to the existing tram network. The second studied case runs from Breukelen, via Maarssen towards Utrecht CS, and will be connected to the Uithoflijn tram line. Figure 0-6 gives an overview of the two lines analysed in the case studies.

While performing the quick scan for the Baarn – Utrecht case, it was found that the population along the corridor would be too large. Moreover, the usage of the heavy rail tracks would constrain the possible frequency. The combination of a potentially large transport demand and a low frequency led to the conclusion that implementation of tram-train is not advisable for the corridor. Therefore, the suitability scan was not performed.



Tram-Train Implementation Support Tool

Quick Scan - Output

	Corridor	Infra	HR Usage	Overall
Can tram-train be applied?	*YES*	*YES*	*YES*	*YES*

Tram-train class	**A / B**
Tram-train mode	**Main**
NOTES	

Suitability Scan - Output

Criterion	Input score	Weighted score	Boundary conditions
1. Population density	*5*	20	✓
2. Multiple corridors	*0*	0	*n.a.*
3. Relation between region and city	*5*	20	✓
4. Attraction centres	*6.6*	33	✓
5. Location of main railway station	*1.4*	4.2	✓
6. Ease of connection	*4.6*	13.8	✓
7. Vehicle width	*7.0*	7.0	✓
8. Vehicle length	*7*	14	✓
9. ROW, Pedestrian area, gauntlet tra	*5.9*	17.7	✓
10. Frequency on tram network	*5*	10	✓
11. Main station & stabling capacity	*7*	14	*n.a.*
12. Vehicle design speed	*3*	6	✓
13. Cycling	*6.0*	12.0	*n.a.*
14. Regional PT	*7*	21	*n.a.*
15. Park & Ride	*6.5*	13	*n.a.*

Frequency & Demand	Result	
16. Frequency analysis	2 *tph*	✓
17. Demand analysis	1000 *pphpd*	✓

Figure 0-5: Screenshot of the T-TIST.

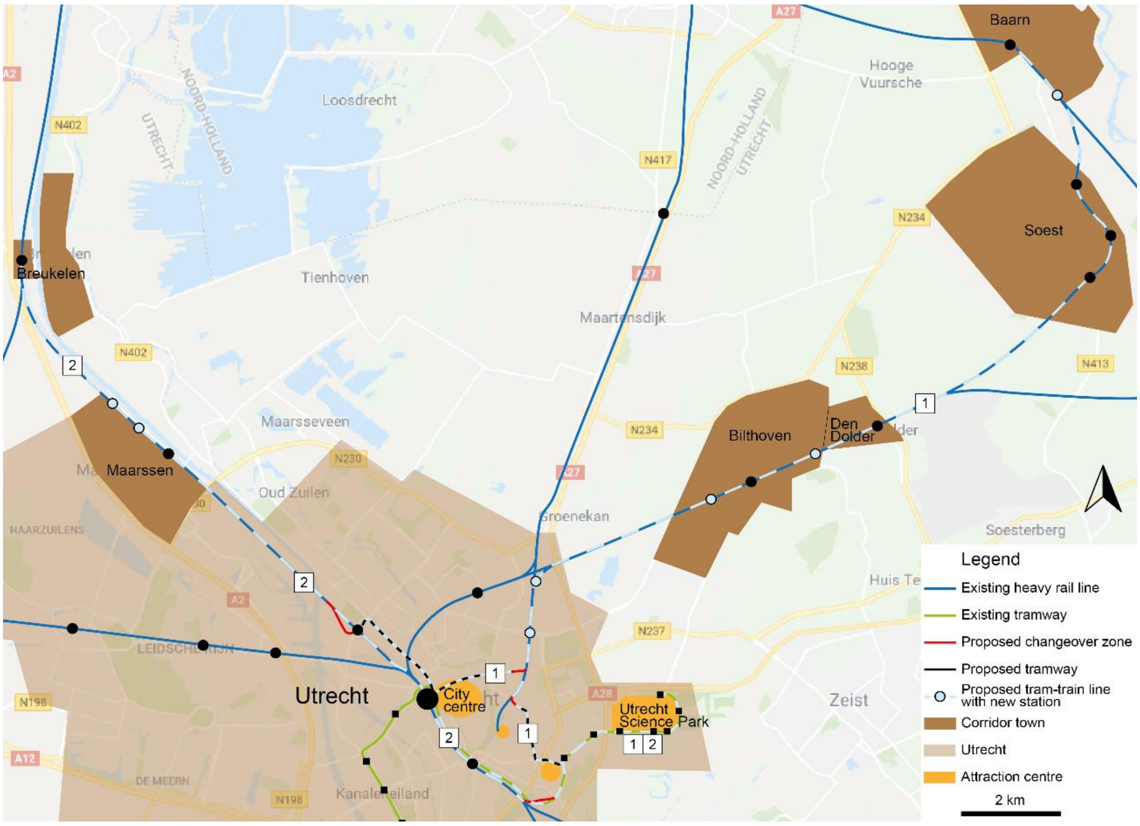


Figure 0-6: Overview of the two case studies. Background: Google Maps.

The second case study focused on another corridor: Breukelen – Utrecht. The quick scan indicated that tram-train could be applied, with shared operations on the heavy railway. Several locations for a connection between the heavy rail network and tram line were analysed. The suitability scan indicated that tram-train is very suitable for the corridor. It is preferable to serve the tram-train at a train platform on the main station. A travel time analysis was performed to reveal the benefit for passengers. The actual travel time between Breukelen and Utrecht Science Park (USP) would remain the same, and even decreases for passengers between Maarssen and USP. Due to the elimination of the transfer, the experienced travel time would be significantly reduced, by up to 35 per cent for passengers between Maarssen and USP.

Overall, the T-TIST was found to meet the set requirements: the tool is usable in an early exploratory project phase, and quickly provides comprehensible results. The required input data can easily be obtained through site visits and publicly available sources. It should be remembered that the tool provides an indication, and that the final output should be interpreted carefully and relative to the local conditions. A critical assessment of the results is always required.

Conclusion & Recommendations

Tram-train has been applied successfully in various cities throughout Europe. An analysis of reference systems showed that tram-train is a flexible mode and can be adapted to many local conditions. Although all analysed tram-train systems can be categorised in four classes, there is no generalised concept of tram-train that is used in each city. In this thesis, a model was developed that works well for urban regions where it is studied to implement a specific concept of tram-train: aiming to connect a tram network in a city to a regional heavy rail network which serves smaller regional settlements. Within this setting, the model can distinguish between cities with and without an existing tram network. In future research, the model can be extended to include other tram-train concepts as well, but also by including cost estimations and assessments of the political and institutional context.

The effectiveness of a tram-train system was evaluated on pre-defined improvement objectives. Overall, tram-train can reduce (experienced) travel times between regional settlements and a city centre. Moreover, tram-train can increase the coverage of the public transport network. Tram-train performs better than buses in terms of sustainability and passenger experience but does not provide additional benefits compared to other rail-bound modes. The ability of a tram-train line to improve the transport capacity is strongly dependent on local conditions, such as available train paths.

Several applicable characteristics of the city, regional corridor and existing rail networks were identified. For the overall possibility of tram-train being successfully implemented, the number of inhabitants per line-km along the corridor and available capacity on the heavy rail tracks were found to be very important criteria. These criteria relate to the potential transport demand and transport capacity. The length of the regional corridor was found to be relevant as well, relating to travel time. The suitability of a tram-train line is determined by assessing fifteen criteria, which are distributed over four categories. The categories indirectly assess the suitability of various parts of tram-train: the regional corridor, the city itself and the rail public transport network. The designed framework can be used effectively to assess variants of a tram-train line and to compare them to existing systems.

The accuracy of the quick scan can be improved by analysing a larger dataset to improve the estimation of the thresholds, and by implementing a more detailed method to assess the served population of a corridor. The accuracy of the suitability scan can be improved by fine-tuning the way the criteria are posed and by further specifying the inputs, so that most scores follow from the same input data type and less normalisation is required.

Contents

Tables

Figures

Glossary

a.t.r.	Above top of rails.
BOStrab	German regulations for operations of tramways
BRT	Bus rapid transit
DRT	Demand responsive transit
EBO	German regulations for operations of heavy railways
GRT	Group rapid transit
IM	Infrastructure manager
IVT	In-vehicle time
MCA	Multi-criteria analysis
NS	Nederlandse Spoorwegen; Dutch Railways
P&R	Park and Ride
pphpd	Passengers per hour per direction
PRM	People with reduced mobility
pt	Public transport
RER	Réseau Express Régional; Parisian suburban railways
ROW	Right-of-way
T-TIST	Tram-Train Implementation Support Tool
TOC	Train operating company
TOD	Transit-oriented development
TSI	Technical Specifications for Interoperability
tph	Trains per hour
USP	Utrecht Science Park
Utrecht CS	Utrecht Central Station
WSM	Weighted-sum method

1 Introduction

This chapter discusses the purpose and contents of this report. First, the background of the topic is described. After that, the problem is stated, and the research objective and question are formulated. Then, the relevance of the research is described, from a societal and scientific point of view. Lastly, the content of the report is presented.

1.1 Background

Many cities are dealing with increasing congestion on roads, but also in public transport. Heavy rail corridors are operated at full capacity near busy stations and main network nodes, while urban tram systems lack direct connections with neighbouring cities or within built-up regions. Even though the public transport system as a whole often provides coverage throughout the region, transfers and congestion on the tracks lead to increased travel times and decreased comfort of commuters. This affects the attractiveness of the public transport, and limits expansion of services. As a result, the car often is a more convenient mode for travellers.

In August 2018, ProRail and Dutch Railways (NS) announced that the Dutch heavy rail tracks are almost fully utilised (ProRail, 2018). Increasing the capacity on highly occupied railway lines and especially at station yards is very difficult, due to operational characteristics of trains (block systems, braking distances). Moreover, expanding stations in densely populated areas often is very expensive or even nearly impossible due to e.g. lack of space (Veeneman, 2018). At the same time, extending existing tram networks into outskirts of cities or even towards neighbouring towns requires additional infrastructure, which is expensive and prone to opposition of local residents. Besides, a tramway towards outskirts and neighbouring cities might not be a competitive travel alternative, as urban trams have a relatively low average speed that results in long travel times (Van der Bijl, Baartman & van Witsen, 2010).

In the present context of sustainability and environmental concerns, electrical powered public transport is favourable over conventional diesel bus systems. For cities with severe pollution issues, cleaner forms of public transport can help relieve the transport system’s burden on a city’s liveability by reducing greenhouse gas and particulate matter emissions. Besides, modern, efficient and ‘green’ public transport systems can also boost the image of a city, which results in increased feasibility of investments from a societal cost-benefit analysis point-of-view.

As a result, many cities talk about light rail projects that should improve accessibility and connectivity between cities. However, light rail is more an umbrella term for many different systems, such as fast or interurban tramways, not fully-segregated metros (e.g. Amsterdam line 51) or premetro (Antwerp). Van der Bijl et al. (2010) position light rail in the centre of a triangle, between tram, metro and train, indicating that light rail can combine characteristics of the individual modes. In line with this research, the following definition of light rail is proposed:

“*Light rail is a rail-bound form of public transport that is used on the scale of the urban region and the city. In contrast to train and metro, light rail is suitable for integration to a certain extent in public space and, if desired, for mixing with regular road traffic.”* Van der Bijl et al., 2018, p19*.*

The triangle is illustrated in Figure 1-1, and on its edges, one finds systems that result from integrating two modes. The main topic of this thesis is the integration of tram and train into a single, combined system: tram-train.

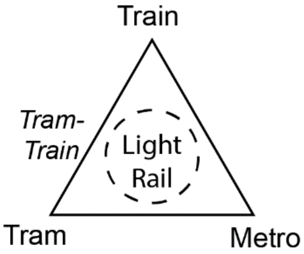


Figure 1-1: Position of light rail and tram-train in relation to tram, metro and train. Adapted from Van der Bijl et al. (2010).

1.2 Problem statement

Theoretically, six system combinations can be made: tram-train, train-tram, tram-metro, metro-tram, metro-train and train-metro, although the last two are not regarded as light rail (Van der Bijl, Bukman & van Oort, 2015). For each of the combinations, the first system continues onto infrastructure of the latter: tram-train is a tram-like vehicle (partly) running on train infrastructure. Karlsruhe is a leading example of tram-train; successful integration of a local tram network with a regional heavy rail network. Following the example of Karlsruhe, several other cities (amongst others Kassel, Mulhouse, Sheffield and Paris) have implemented or are developing tram-train systems.

However, integrating two rail systems leads to technical challenges regarding the many interfaces between the two. Each city (and country) has its own system characteristics, which makes it difficult to copy solutions of other cities one-on-one. For each challenge encountered, engineers should find a suitable solution. As a concise overview of technical solutions does not yet exist, this might lead to costly and time-consuming trial-and-error solution seeking. The effort can be saved by first determining the applicability of tram-train for urban regions, after which the technical feasibility can be studied.

1.2.1 Research objective

The goal of the research was to develop an evaluation model that determines whether tram-train can be applied in an urban region and whether it is a suitable solution to achieve desired operational improvements. Inputs for the model include data on characteristics of a city (an extension to works of Naegeli, Weidmann & Nash, 2012; Van der Bijl & Kühn, 2004) and properties of existing tram and heavy rail systems. To aid in determining the technical feasibility, a library of technical solutions was developed.

The model and library were made usable in practice by developing the model into a decision support tool. The tool advices on operational applicability and technical feasibility of tram-train systems with a connected technical solution library. The outcome of the tool is aimed at transit authorities (such as Transport for London) and should be useable in phases in which various alternatives for improvements to public transport (both network capacity and passenger flow) are researched (Figure 1-2). Therefore, the tool might also be used by transport engineering firms and consultancies, working for transit authorities.

Figure 1-2: Position of tool (outlined in red) in planning process.

1.2.2 Research question

The main research objective forms the basis for the main research question. The answer to the main research question is found by answering several supporting sub-questions.

> *How can applicability of tram-train in an urban region be evaluated using a generalised approach, based on both public transport and city characteristics?*

1.2.2.1 Sub questions

- What are objectives for improvements in (sub)urban public transport? (§2.1)
  - What measures could be taken to achieve these objectives? (§2.2)
- How can a tram-train system be defined in this research? (§4.1)
- What are the operational characteristics of tram-train systems, in terms of capacity, stop spacing, speed, etc? (§4.3.2)
  - How do tram-train systems compare to ‘traditional’ modes? (§4.3.2)
- What are the (operational) advantages of integrating tram and train systems? (§4.4)
  - What are the disadvantages? (§4.5)
- What (socio-economic and urban planning) characteristics of an urban region make the region suitable for a tram-train system? (§4.6)
- Which challenges arise when urban rolling stock is to be used on heavy rail, and vice versa? How can these be solved? (§5.4; §F.1; F.2)
- Which challenges arise when heavy rail and tramway infrastructure are connected? How can these be solved? (§5.4; §F.2; F.3; F.4)
- What are the differences in operational aspects between tram and heavy rail systems? How are these solved in tram-train operations? (§5.4; §F.5; F.6; F.7)
- How can the acquired knowledge of tram-train be captured in an evaluation method? (§5)
- How can the developed model be transformed into a usable tool? (§6, §7)

1.3 Societal and scientific relevance

Societal relevance

With a growing economy, there is much need for effective mobility in cities. Although light rail is often called for as a solution, the actual implementation will be based on the principles of tram, train and metro; systems that already exist. Utilising the existing infrastructure more efficiently can provide a better public transport system without the expenses for new systems.

In the Netherlands, over the past years some of such tram-train ideas have been trialled, but were not implemented (RijnGouwelijn), or were politically abandoned before the construction phase (RegioTram Groningen), but there is also the example of the well-developed RandstadRail that performs better than expected. Also, in Germany, tram-train is a proven concept with several implemented systems showing increases in passenger numbers.

Scientific relevance

There is plenty of documentation on ‘traditional’ modes in urban public transport (e.g. HiTrans, 2005; Vuchic, 2005; TRB, 2013), but little is documented about typical system parameters of tram-train systems. In this thesis, the system parameters of tram-train are determined. Moreover, there has been limited research into what makes tram-train a good investment in public transport. Van der Bijl et al. (2015) describe the lessons learned from several tram-train and light rail projects worldwide. Both Van der Bijl & Kühn (2004) and Naegeli et al. (2012) created checklists for implementation of tram-train, with the latter mostly focussing on German systems. Both checklists focus on a wide range of criteria, ranging from institutional context (not discussed in this research), characteristics of city and urban region (discussed in chapter 4 of this thesis) to technical issues (discussed in chapter 5 of this theses). However, the criteria are discussed only briefly and on a very qualitative level, leaving a lot of room for interpretation. The model that was developed in this thesis provides a more thorough and specified analysis of city characteristics in determining the suitability of tram-train for a region, by utilising the existing knowledge of traditional modes and applying this on tram-train.

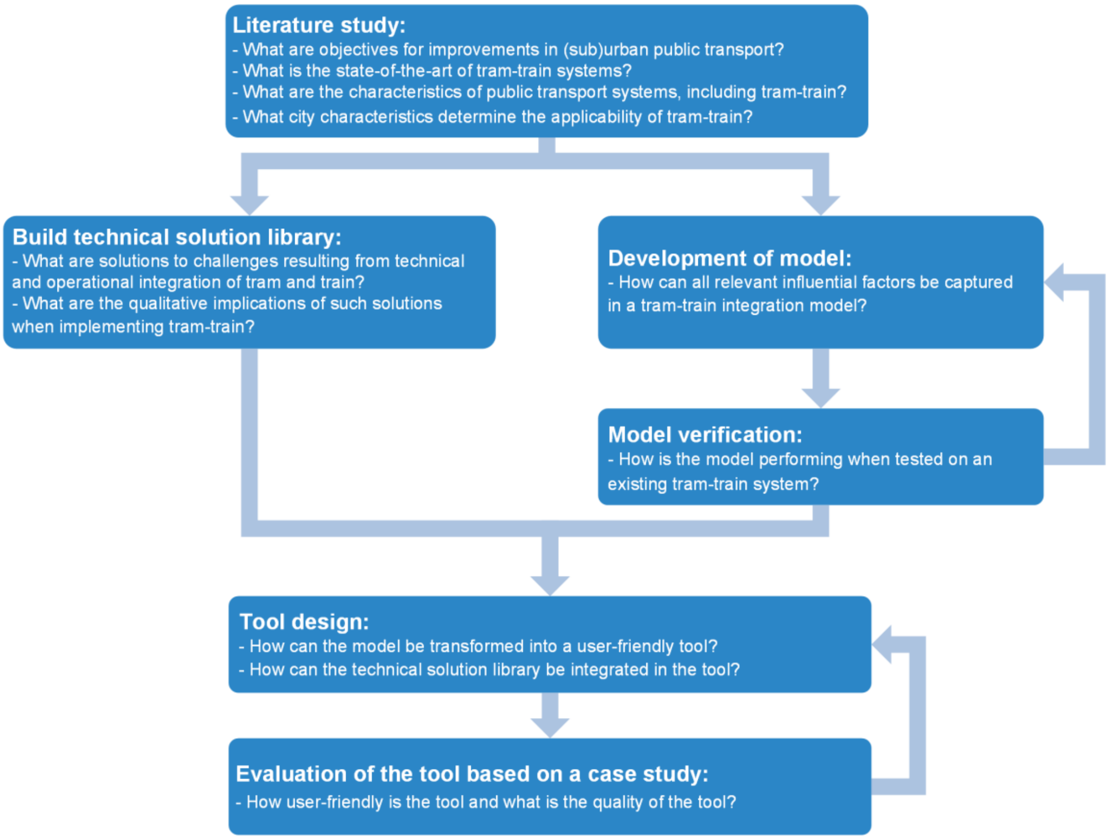
Regarding the technical implementation, research has been done on integration of some of the interfaces (Crosbee, Allen & Carroll, 2016; Muller, 2015; Novales & Conles, 2012). The technical solution library aims to fill this gap by collecting past lessons and providing a technical integration framework.

Relevance for Mott MacDonald

This research is conducted under supervision of Mott MacDonald, a global engineering consultancy in the fields of transportation, buildings & infrastructure, water, power, and environment. The company is involved in many rail expansion projects around the world and the results of this research aid the company in two ways. The library of technical solutions supports teams working on tram-train projects in finding adequate solutions to integration challenges. Secondly, the model can aid in studies on a planning level, by determining the suitability of tram-train as a mode in certain urban regions.

1.4 Research approach

Figure 1-3 shows the taken research approach. First, an extensive literature study of scientific literature, interviews, and reference systems was performed, with which several of the research questions were answered. Based on the literature study, the evaluation model and technical solution library were developed. The model was verified by applying it to an existing tram-train network, to see whether the model yields reliable results. Here, a feedback loop is included. If the verification step does not prove to be successful, alterations to the model should be made. Then, the verified model and library were combined into a practical tool for use on new cases. The effectiveness of the tool was evaluated by performing a case study, which feeds back to the tool. Improvements resulting from the case study were included in the tool when possible or left as potential future improvements to the tool.



Literature study:
- What are objectives for improvements in (sub)urban public transport?
- What is the state-of-the-art of tram-train systems?
- What are the characteristics of public transport systems, including tram-train?
- What city characteristics determine the applicability of tram-train?

Build technical solution library:
- What are solutions to challenges resulting from technical and operational integration of tram and train?
- What are the qualitative implications of such solutions when implementing tram-train?

Development of model:
- How can all relevant influential factors be captured in a tram-train integration model?

Model verification:
- How is the model performing when tested on an existing tram-train system?

Tool design:
- How can the model be transformed into a user-friendly tool?
- How can the technical solution library be integrated in the tool?

Evaluation of the tool based on a case study:
- How user-friendly is the tool and what is the quality of the tool?

Figure 1-3: Research approach.

1.4.1 Characterising an urban public transport system

Different public transport modes fulfil different purposes. Some types are designed to transport people over long distances at high speeds, while others are built to serve as many people in an area as possible. Table 1-1 describes the network and operational parameters of a mode. These operational parameters will be referred to throughout this report, as to be able to relate various parts of the research together.

Table 1-1: Operational parameters.

Parameter	Unit	Description
Average speed	km/h	The length of a line divided by the time necessary to cover it.
Stop spacing	m	The average distance between two stops.
Dwell time	s	The time a vehicle spends at a stop.
Line length	m	The average length of a line.
Network structure	--	How a network is oriented in a city. Radial, Grid, Tangential, point-to-point
Peak capacity	pphpd	The transport capacity of a line per hour, in one direction.
Minimum headway	s	The shortest possible time-separation between two vehicles. Headway also determines frequency: f = 1 / h

Parameter	Unit	Description
Degree of separation in traffic	--	Vuchic (2005) distinguishes 3 types of traffic separation (right-of-way, ROW). Systems can make use of multiple types. i. ROW A: Paths used exclusively by transit vehicles, with full priority over road traffic at level crossings. ii. ROW B: Partially separated tracks, shared intersections with regular traffic. iii. ROW C: Urban streets with mixed traffic.
Integration in city	--	The degree to which a system can be integrated in urban design: i. Integrated (moderately or well) ii. Separated iii. Closed

1.5 Contents of the report

The report is structured as follows: Chapter 2 describes the context of public transport in urban regions, the demand. The perspectives of stakeholders are described, and these are translated into specific measures for improvements in public transport. Chapter 3 lists the supply side of public transport in urban regions. A quick scan into available modes is made, with a framework for comparing the modes. Chapter 4 describes tram-train, by illustrating the state-of-the-art according to several projects, listing the (dis-)advantages of tram-train and describing typical regions in which tram-train is or can be operated. Chapter 5 covers the development and verification of the model. Chapter 6 briefly describes the construction of the tool, which is tested on a case study in chapter 7. Lastly, chapter 8 and 9 state the conclusion, discussion and recommendations of this research.

2 Public transport organisation

This chapter starts with describing the demand side for public transport from a user's, operator's and government's perspective. For each of these stakeholders, the perspectives are translated into specific objectives to increase the attractiveness or viability of public transport. To meet the objectives, several improvement measures are described.

2.1 Stakeholders in urban public transport

In urban public transport, three main groups of stakeholders are involved: the users of public transport, the operators, and the government (Figure 2-1). There are other stakeholders, such as residents in the vicinity of corridors, but their views are assumed to be included in the government's or user's perspectives. Each of the stakeholders has specific desires, which might be conflicting when regarded from all three perspectives. Finding a balance between the demands is key when setting up public transport networks.

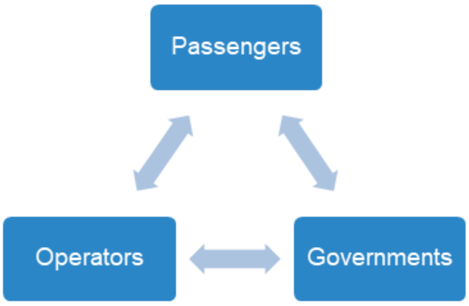


Figure 2-1: Stakeholders in public transport.

2.1.1 Public transport from a passenger's perspective

Public transport ultimately serves the traveller, who uses the service. Therefore, the traveller should have an incentive to use public transport. Users of public transport can be categorised in two groups; those with alternative means of travel and those without alternative means (Ceder, 2007; Teodorović & Janić, 2016). Ceder (2007) splits the use of public transport for people with an alternative into two cases. First, there are people who use public transport if the provided service is of an acceptable level. Secondly, there are people who still prefer the automobile over public transport with an acceptable service. They require a more comfortable trip than they would be able to make by car. Whether a provided service is acceptable depends on several criteria. Acceptance criteria for passengers can be related to public transport system parameters, as shown in Table 2-1.

Comfort criteria such as on-board special features and attractive interior vehicle design are less relevant in urban public transport, where travel times are relatively short (Ceder, 2007). On the other hand, Teodorović and Janić (2016) note that public transport can provide additional comfort over automobiles as for instance the nuisance of finding a parking spot or sitting in traffic jams is removed.

Table 2-1: Relation of acceptance criteria and system parameters.

Passenger acceptance criterion (Ceder, 2007)	System parameter
Travel time	Average speed
Walking distance in origin - destination chain	Stop spacing, line spacing
Waiting time	Frequency
Tariffs	--
Smooth and synchronised transfers	In urban PT: Frequency*
Acceptable on-time performance	Reliability: Amount of shared / segregated track
Seat availability	Vehicle size, frequency
Off- and online information system	--

* In urban public transport, transfer times are closely related to frequencies. When high frequencies are offered, waiting times will be short. Therefore, specific synchronisation of transfers is not required. For higher-level public transport, where headways range between twice per hour to once every two hours, synchronised transfers largely depend on timetabling and reliability.

Peek and Van Hagen (2002) developed a Maslow pyramid for public transport quality (Figure 2-2). This pyramid shows the fundament for public transport (safety and reliability) on which, in decreasing order of importance, other quality factors are positioned. Speed and convenience are regarded as dissatisfiers: if they are okay, they are not noticed by passengers. However, if speed and convenience are insufficient, passengers will avoid public transport. Travel comfort and experience are satisfiers. If there is no enhanced comfort or experience, it will not be noticed by passengers. If measures are taken to improve these factors, passengers will be positively influenced.

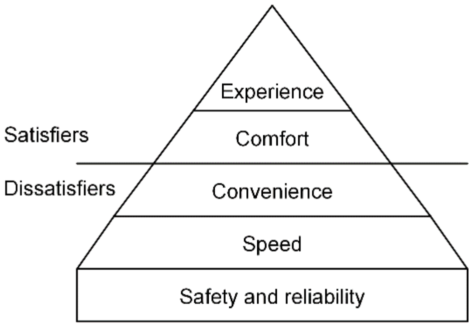


Figure 2-2: Maslow pyramid of public transport quality factors. Peek & Van Hagen (2002).

2.1.1.1 Travel time components

The time it takes a passenger to make a trip with public transport consists of several steps. As public transport is operated along fixed routes, passengers should often transfer to get near their destination. A transfer consists of two steps; walking from the first vehicle to the platform of the second and waiting for the second vehicle to arrive. When a transfer between modes is made, there can be a large variation in walking distance. Small, efficient stations have short walking distances between modes (or a bus and tram stopping at the same platform), while in large public transport nodes walking times can be over 5 minutes. A typical trip process is shown schematically in Figure 2-3. The components of a trip are outlined by Balcombe et al. (2004) and described in Table 2-2.

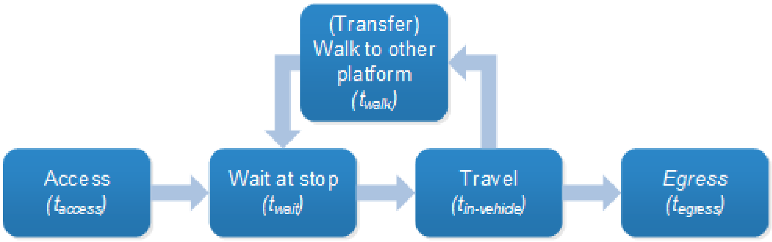


Figure 2-3: Typical trip scheme. Adapted from Van der Bijl et al. (2015).

Table 2-2: Description of travel time components.

Trip component	Description	Operational parameters
Access, Egress	The time it takes to get from origin to a stop, and from the last stop to the destination.	Stop spacing, mode choice
Wait	The time spent between arrival at a stop and departure of the vehicle. This also includes time spend waiting at the origin before departing to a stop (Van der Bijl et al., 2015).	Frequency
In-vehicle	The time spent in a vehicle.	Average speed
Transfer	Transferring from one vehicle to another: walking to the other platform and waiting for the next vehicle to depart.	Frequency, transfer stop spacing*

* Stop spacing in a transfer refers to the distance between the platforms or modes.

2.1.1.2 Accepted and experienced travel time

Hupkes (1982) found that the total time people spend on travelling each day is constant; between 65 and 85 minutes, with an average of 75 minutes. Besides commuting, this average also includes travel for leisure or shopping. A more recent, exploratory study (Milakis & van Wee, 2018) shows differences in average and acceptable commute times for different modes. For public transport, they found that the average actual public transport commute time in Delft (NL) was 55.6 minutes, while the respondents found 42.5 minutes an acceptable commute time.

Wardman (2004) notes that people value time differently while in different phases of their trip, which is valuated relative to in-vehicle time (IVT). Due to different experienced total travel times, it is possible that commuters prefer a route with a longer actual travel time over a shorter route with less comfort. Table 2-3 lists a brief overview of results of several studies into the time valuation of various trip segments.

Table 2-3: Time valuation relative to IVT for various trip segments.

Trip segment		Result	Source, notes
Access, Egress, Transfer	Walking	IVT x 1.68	Wardman (2004), GB, meta-study.
	Access to rail, average	IVT x 1.31	Wardman (2004), GB, meta-study.
	Access & Egress	IVT x 1.5	PBL (2009), NL.
Waiting		IVT x 1.76	Wardman (2004), GB, meta-study.
		IVT x 1.4	PBL (2009), NL.
In-vehicle	Seated, Load factor 60 – 100%	IVT x 1.15	Wardman & Wehlan (2010), GB, meta-study.
	Seated, Load factor > 100%	IVT x 1.5	Wardman & Wehlan (2010), GB, meta-study.
	Standing	IVT x 2.4	Wardman & Wehlan (2010), GB, meta-study.
	Standing	IVT x 1.18 – 1.55	Tirachini et al. (2016). Singapore, RP-study.

Trip segment		Result	Source, notes
Transfer	Total transfer	16-34 minutes 31 min average	Wardman (1998). Includes walk and wait time. 16 minutes for suburban, 36 minutes for rail.
		6-17 minutes	Haarsman (2012), NL, SP-study, train-train transfer.
		13 minutes	De Keizer & Hofker (2013), NL, ideal train-train transfer.
		34 minutes	De Keizer & Hofker (2013), NL, average train-train transfer.
	Penalty only	8 minutes	PBL (2009), NL.

Notes: SP-study: stated preference study; RP-study: revealed preference study.
Wardman (1998) as cited in Balcombe et al., (2004).

From Table 2-3, is concluded that transfers and waiting have a large influence on the experienced travel time. Moreover, there are differences between time valuations in different countries. Next to quantitative values, it has been found that transfers on short journeys are a greater disutility than on long journeys (Wardman, 2001; Haarsman, 2012).

2.1.1.3 Conclusion

To attract more passengers to public transport, it is important to consider the criteria of acceptable service. Improving the related system parameters will yield a more attractive system which provides a better alternative to other modes. Shortening travel and access time are the most effective (Van Nes, 2016), and can be achieved by providing high frequencies and direct services. However, it should be kept in mind that the attractiveness of other modes is variable as well. Investments made to benefit public transport can also affect the level of service of the road network. Naturally, ticket price also influences the attractiveness of public transport.

2.1.2 Public transport from an operator’s perspective

While individual passengers make choices that will lead to most benefits to them, public transport operators can be private companies and as such strive to make profit. However, providing public transport is not always a profitable business. Operational costs are high and low-demand lines generate little revenue. Tariffs cannot be increased to cost-beneficial levels, as this would make public transport no financial alternative to private transportation. Adequate public transport for everyone is regarded as a government’s responsibility. Therefore, governments provide subsidies to public transport operators (UN-Habitat, 2013). Governments can use various methods to award concessions to operators. Depending on the awarding method and the subsidies provided, an operator will have more or less incentive to improve its services.

2.1.2.1 Heavy rail

In Europe, train operating companies (TOC’s) are separated from the infrastructure managers (IM’s). A TOC pays a track access charge to use the tracks of an IM, which uses the money for maintenance and small improvements. For some lines, private companies can buy capacity and operate trains for profit, while on other lines governments still use a competitive tendering strategy to ensure acceptable services can be offered.

IMs can have incentives to invest in capacity. At large stations, track capacity is limited, while on open track, capacity is seldom fully used (ProRail, 2018). This is due to the time required for departure procedures and for trains to clear switches and free paths for the next train. Some improvements can be achieved by optimising departure procedures and positions of signals (Goverde, 2016). However, stations will remain to be constraints in track capacity. As stations were built at edges of city centres long ago, expanding cities have ‘swallowed’ stations over the years, leaving very little room for expansion. Without additional infrastructure, it is very difficult to increase the throughput without decreasing robustness of timetables (Veeneman, 2018a).

Expansion of stations in densely built-up areas or building new tracks is extremely expensive and cannot be paid by track access charges alone. Governments are still responsible for funding these improvements.

2.1.2.2 Conclusion

For public transport operators, profitability is one of the most important key performance indicators. Therefore, public transport operators are keen to improve public transport if it leads to increased profitability. This can be achieved through more efficient operations (transporting the most passengers with the least number of trips) or increasing the amount of received subsidy (Van Nes, 2016).

2.1.3 Public transport from a government's perspective

It was noted that public transport is often seen as a government's responsibility. The need for public transport from a government's perspective eventually follows from higher-level strategic (planning) decisions. These strategic decisions are taken at national or regional/metropolitan government levels and are often part of long-term visions (Van Oord, 2018). Figure 2-4 illustrates how problem definitions for public transport follow from these strategic decisions.

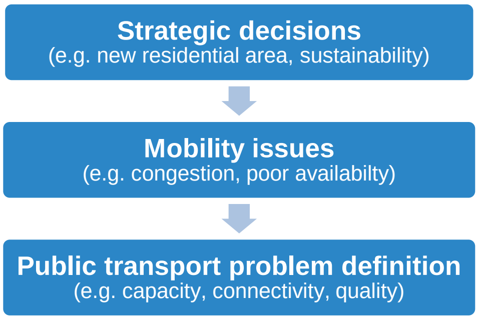


Figure 2-4: From strategic planning to public transport.

Strategic planning decisions follow from city development plans. Cities might want to expand their size and number of inhabitants or available jobs by adding new areas at the borders (such as the Zuidas, a business district in Amsterdam). In other cities, the attractiveness of areas is increased by renewal or improvement of commercial areas. Strategic planning can also be the redistribution of housing areas over an urban region, developing new residential areas in neighbouring towns, while shifting the focus of the main city more towards providing jobs and leisure.

Furthermore, governments are more and more concerned about the environment and climate change and as such strive for sustainability goals. These goals often include reduction emissions of greenhouse gasses. The US Environmental Protection Agency states that in 2016, 28 per cent of greenhouse gas emission is attributed to transport (EPA, 2018). In the EU, 44 per cent of greenhouse gas emission in transportation comes from passenger cars (EEA, 2017).

These strategic decisions can lead to issues with mobility. New residential or work areas lead to new flows of commuters and traffic. Improved commercial zones become more appealing and attract additional shoppers. Population and economic growth can also lead to increased strain on road networks and congestion has a bad influence on attractivity of areas. Poor availability of mobility can also be an issue that governments want to address.

Public transport can be a solution to mobility issues. However, investments in public transport are costly. Especially rail-bound modes have very high capital expenditures. The infrastructure is more expensive than regular roadways and especially rail vehicles are much more expensive than buses. It is important to define the desired public transport improvement objectives in line with the mobility issues, to prevent spending money ineffectively.

Government's influence on operational parameters.

Governments set the legal framework in which public transport is operated. This can influence operations due to minimum safety requirements but might also limit alternatives due to noise or line-of-sight regulations.

2.1.3.1 5E's framework

Van Oort, Van der Bijl and Verhoof (2017) have come up with a framework to determine the social cost benefit of rail infrastructure, by looking further than merely expected numbers of passengers and travel time gains. By taking the societal cost benefit into account, higher investments can be justified. The framework consists of 5E's: Effective mobility, Efficient cities, Economy, Environment and Equity.

Effective Mobility

Robustness of the network increases the availability of the network under disrupted conditions. Infrastructure for a new line can provide possibilities for detours for existing lines, which can be useful if parts of the network are obstructed after e.g. an accident, a broken vehicle or damage to the facilities. Moreover, travellers experience a value of time for their trips. Reliability of the travel time (i.e. less variation in trip time) improves service for passengers, but also reduces exploitation costs as less reserve vehicles are required (Van Oort, 2011). Thirdly, comfort plays a role. Research of Bunschoten et al. (2013) shows that a 'railbonus' exists: travellers favour a tram over a bus. Trams can attract 5 to 10 per cent more passengers than a bus line, while keeping the same frequency and speed.

Efficient Cities

Public transport provides an efficient use of public space. Compared to the same surface area of cars, a tram or bus can transport many more passengers. Furthermore, space otherwise required for parking in city centres can be utilised for more beneficial purposes. This way, cities can be condensed. This can increase attractivity of compact, central areas and prevents expansion of outskirts of cities. Moreover, public transport gives structure to a city. Railway lines are visible and, if designed thoroughly, need not be a barrier. It is clear where rail vehicles will be travelling, and by reducing the number of cars, public transport can improve traffic safety. In all, public transport can increase the quality of life and as such is used as a policy measure (Van Oort et al., 2017; OV-bureau GD, 2017).

Economy

High-quality public transport, and especially railway lines, increase real estate value. Railways have a definite location for decades, and around main nodes ground prices and real estate values can increase by 2 to 10 per cent. Decent public transport also increases the accessibility of shopping areas, which increases sales revenue. Lack of public transport can even limit economic growth and urban development (Van Oort et al., 2017).

Environment

Especially in cities and due to heavy traffic, hot-spots with high levels of particulate matter occur. For all types of public transport holds that the larger vehicle capacity leads to reduced energy usage and emission per passenger kilometre compared to private vehicles (Kay, Morris & Hill, 2011). The combination of public transport as main travel mode, combined with cycling as first and last mile transport has a clearly positive impact on the environment. As mentioned for *efficient* *cities*, the reduced land use for public transport compared to private vehicles also has environmental benefits.

Equity (and health)

Lastly, well-designed public transport networks can increase equity in cities. Accessible (cheap) public transport that connects economically lesser developed areas to for instance city centres ensures that those who cannot travel by car or bike get more opportunities. The combination of active modes and public transport has positive influences on health (Van Oort et al., 2017). Upgrades of public transport can also bring improvements to social safety. The Hoekse Lijn (Rotterdam, NL), a for NS unprofitable regional line, used to be neglected, with deteriorating track conditions and poorly maintained stations. At night, stations were ill-lighted, and trains ran at low frequencies. In 2019, the line will be reopened as an extension to the metro network of Rotterdam, with additional stations and higher frequencies. After the modifications, ridership is expected to grow by 40 per cent (Kats, 2018).

2.1.3.2 Conclusion

For governments, public transport can serve multiple causes, which are sometimes contradictory. On one hand, authorities aim to minimise subsidy to operators, but at the same time need to provide maximal social benefits. Providing public transport to areas with very low population densities is important for equity but will not be profitable for an operator. Also, increasing the patronage can be a goal, which might not be possible for the lowest subsidy. However, all the aforementioned goals aim at minimising total costs, which is seen as the main objective for authorities (Van Nes, 2016).

2.2 Measures for improving public transport

In the previous section, the objectives for good public transport were identified for passengers, operators and governments. These objectives can be achieved by implementing certain measures.

2.2.1 Efficient public transport: improving line capacity

As ridership increases, there is a point in which all vehicles are used to their design capacity. There will still be some slack in the system, as the design capacity is lower than the theoretical maximum capacity, but it will be difficult to provide comfortable journeys for all passengers. Ultimately, it is necessary to add new lines, or increase the capacity of existing lines.

According to White (2009), line capacity (C_{line}) of a railway depends on three variables, which can be modified to increase the capacity.

- Carriage/unit capacity (C_{car}): This can be increased by replacement by larger carriages or units, for instance by widening vehicles. Many old tram systems have trams with a width of 2.40 meters, while modern light rail vehicles are up to 2.65m wide. Figure 2-5 shows the effect of vehicle width and length on the capacity of a tram. In some cases, increasing the height or width of carriages can be difficult due to loading gauge restrictions. Lastly, carriage capacity is increased when less seats and more standing space is provided, which is common in urban public transport systems.
- Train length (n_{cars}): The number of carriages or units that make up one train. Extending the train length is only possible if the platforms along the line are long enough to accommodate the additional cars. Generally, platforms can be lengthened, but in tunnels or on viaducts this might not be possible due to space limitations or excessive cost.

- Trip frequency (*f*): If the capacity of trains cannot be increased any further, the line capacity can be increased by running more trains per hour. On urban tram lines, where there is no train-protection system in place and operation is homogeneous and on sight, adding more vehicles is relatively easy. On heavy railways where train protection systems are in place, decreasing headways is only possible until the protection system's capacity is reached.

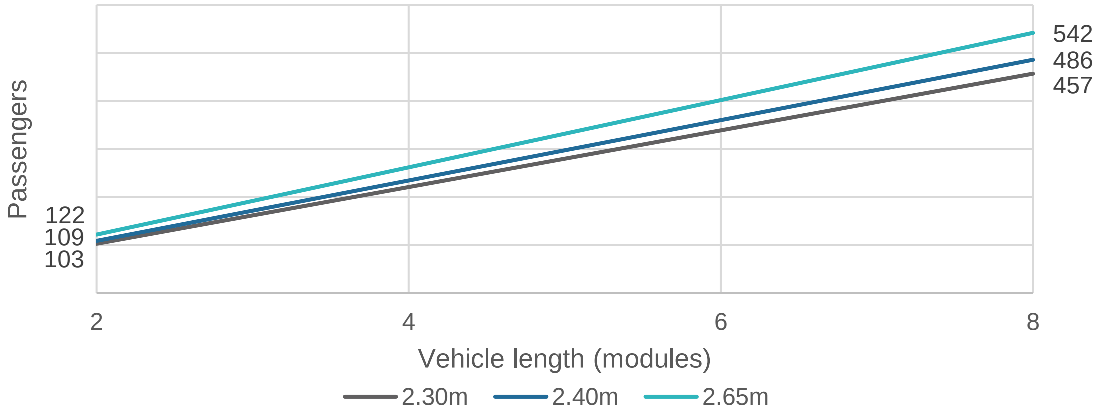


Figure 2-5: Relation between vehicle width and capacity. Adapted from Siemens (2016).

The line capacity can be calculated with equation (1). Peak capacity is calculated by taking the capacity of the largest carriage, longest train and highest frequency.

$$C_{line} = C_{car} * n_{cars} * f \qquad (1)$$

Increasing frequency or adding additional multiple units are flexible measures of increasing capacity. These measures are useful for providing additional capacity during rush hour, and saving operational expenses (drivers, energy, wear and tear) during off-peak hours.

According to Vuchic (2005), sometimes it is sufficient to increase the capacity on parts of a line. For instance, in a peak direction, or on certain sections of a line. Therefore, it is possible to schedule short-turn runs. The short-turning vehicles will only operate on the busy section. To provide robustness at the end of the short-turn trip, some facility for storing vehicles should be present. If short-turning vehicles return directly, the holding facility may be omitted, but infrastructure should allow for turning.

2.2.1.1 Bunching

A downside of very short headways is the risk of headways becoming irregular, so-called bunching. Irregular headways of buses and trams on shared infrastructure can occur because of disturbances during operation. Common disturbances include congestion, stops with large numbers of boarding/alighting passengers and waiting at signalised intersections. Less common disturbances are traffic incidents, and driver characteristics also cause variability in driving times. When short headways are maintained, these irregularities can lead to bunching. When bunching occurs, two vehicles form a pair that effectively operates as one vehicle (Teodorović & Janić, 2016).

2.2.1.2 Capacity of heavy railways

On railways with block system signalling, the capacity is limited by the block times, which result from vehicle speed and block length. Capacity is determined according to UIC leaflet 406 (UIC, 2013). All train paths on a line section are compressed to minimum headway times, while maintaining the train sequence. The capacity is the percentage of time required to operate all trains in the compressed diagram (minimum infrastructure occupancy time plus additional times), relative to a defined time period. Additional times are times required to secure the quality of operations (UIC, 2013).

Utilising the full capacity of a railway section leads to reduced punctuality, as there is no room left for recovery of disturbances. The higher the capacity utilisation, the lower the buffer time in between trains. This leads to a high risk of knock-on delays and low punctuality, as shown in Figure 2-6. Pachl (2014) notes that from experience of European railways, daily consumed capacity (24 hours) should not be significantly higher than 50%, while 80% can be consumed during a 4-hour peak period.

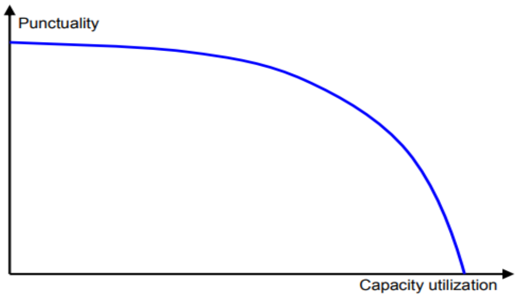


Figure 2-6: Relation between capacity utilisation and punctuality. Landex et al. (2006).

Capacity is lower when there is mixed operation of direct and stopping services without overtaking possibilities. If both services have the same maximum speed, the direct service will catch up with the stopping service each time the latter reaches a station, as visible in Figure 2-7. Adding additional tracks eliminates this issue, but in dense urban areas the space required for a four-track railway might not be there. A cheaper, less space-consuming solution is to only add tracks at stations. Direct services can overtake stopping services while these are dwelling. A downside of passing tracks merely at stations is the increased dwell time of stopping services, which results from the required time separation between trains.

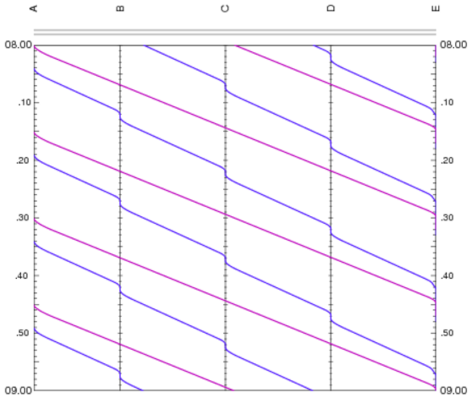


Figure 2-7: Heterogeneous traffic. The direct service (purple) approaches the local service (blue). Goverde (2016).

2.2.2 Attractivity and competitiveness: shortening travel times

Uncompetitive travel times of public transport cause travellers to choose for other modes of transport. Therefore, improving travel times is an objective when (re)designing public transport systems. Besides planned times, the reliability of a service also influences certain steps of a trip process (Van Oort, 2011).

2.2.2.1 Access- and egress times

Access and egress time can be shortened by decreasing the stop spacing. However, decreasing stop spacing leads to a decrease in operational speed due to the extra dwells (Vuchic, 2005).

2.2.2.2 Waiting times

For headways shorter than 10 minutes, waiting time is equal to half the headway. Therefore, waiting time can be shortened by decreasing the headway. For lower frequency services, passengers plan their arrival at the station (Vuchic, 2005). Figure 2-8 shows the average wait time at stations as a function of headway. Increasing the frequency (e.g. from 2 to 3 vehicles per hour) still improves the waiting time at less frequent services. Even though waiting time at the station is constant, passengers spend some time at the origin, waiting to leave for the station (Van der Bijl et al., 2015; PBL, 2009).

Van Oort (2011) notes that if a vehicle departs earlier than some margin before the planned departure, the waiting time becomes equal to the headway. In that case, passengers must wait for the next vehicle. Also, it was found that very short headways can lead to bunching.

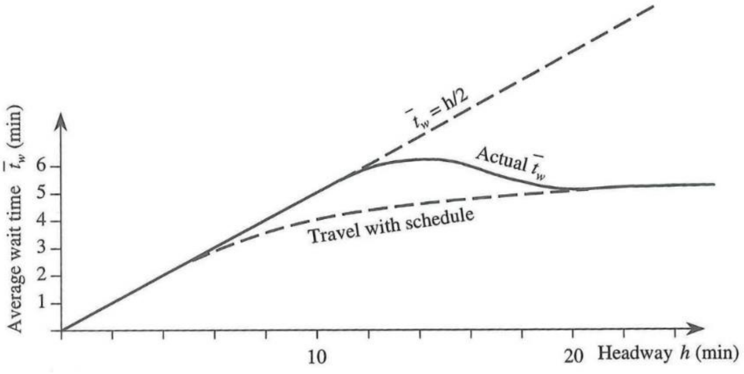


Figure 2-8: Average passenger waiting time as a function of headway. Vuchic (2005).

2.2.2.3 Improving in-vehicle time

The in-vehicle time can be improved by increasing average vehicle speed, which depends on dwell times, number of stops and achieved running speeds (Vuchic, 2005). According to HiTrans (2005), the maximum allowed speed and distance between stops define, to a large extent, the operational speed. Improving these factors leads to the greatest decrease in travel time.

Stopping patterns

Reducing the number of stops (increasing stop spacing) will increase the average speed, but negatively influences the access and egress times. For longer lines, there is a trade-off between frequent stops and high speeds. Stopping at each station lengthens trips so much that competitiveness of public transport decreases in favour of car usage. Adjusting stopping schedules can shorten travel times. Generally, three types of stopping regimes exist, based on major and minor stations. All services stop at the major stations to provide transfer possibilities (Vuchic, 2005). The most common type on train lines is diversification between local and express services. Local services stop at all stations, while express services only call at major stations. Zonal operation is another strategy and uses the local/express service strategy to reduce travel time for destinations further from a main point, which is useful towards main attraction centres. Figure 2-9 shows these two strategies. In section 2.2.1.2, it was found that heterogenous services require overtaking possibilities or lead to longer headways. The third strategy, skip-stop operation, is not discussed.

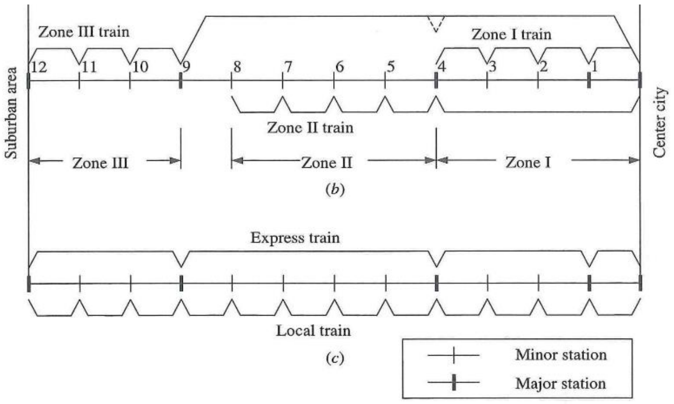


Figure 2-9: Zonal operation (b) and local/express operation (c). Vuchic (2005).

Dwell times

Dwell time is the time that a vehicle spends at a stop. For heavy rail, dwell times are often defined in the timetable (but can still be improved by considering these characteristics), while for urban transport dwell times are as long as it takes for all passengers to board/alight. Dwell times depend on the following characteristics:

- Interior vehicle circulation: the easiness of moving around in a vehicle. In highly-occupied vehicles, it can be difficult to move through the crowd (Vuchic, 2005). Increasing vehicle capacity (more standing space) or frequency reduces vehicle occupancy and improves circulation.
- Boarding- and alighting speed:
  - The number of available doors and their width (Vuchic, 2005; TRB, 2013).
  - Matching platform and vehicle floor heights: Van der Bijl et al. (2015) found that the average dwell time and standard deviation decreased when vehicle floor and platform height are the same. In TRB (2013), it was found that the presence of doorway steps approximately doubles the boarding and alighting time per passenger.
  - Fare collection: Allowing passengers to board and alight through all doors saves time. Most benefits can be achieved by collecting fares at the platform (Van der Meijs, 2015).
- Platform design:
  - The location and presence of multiple platform entrances: this can spread passengers over the platform. It is applicable for systems with long vehicles and when boarding is allowed at all doors (Vuchic, 2005).
  - Platform width: wider platforms allow better flows of passengers (TRB, 2013).

Running times

Running time is the time spent by a vehicle while in motion. The lowest possible running time is achieved when a vehicle can travel at a constant, high speed. According to Vuchic (2005), running times can be decreased by applying any of the following measures:

- Improving acceleration and deceleration characteristics: urban public transport vehicles stop often. Besides at stops, they are stopped by traffic lights. Vuchic (2007) notes that rail-bound vehicles are generally limited by the adhesion between rails and wheels; increased engine power does not necessarily improve acceleration. Reducing vehicle weight and powering more axles are ways of improving acceleration and deceleration characteristics.

- Traffic signal prioritisation: there exist systems that allow emergency and public transport vehicle to announce their arrival at a signalised intersection. The traffic controlling equipment will prioritise the requesting vehicles, by extending green phases or shifting phase sequences. However, traffic light prioritisation does not work on corridors with very short headways, to prevent extreme green phase reduction for other traffic.
- Providing full priority on intersections: for tramways on fully separated tracks, full priority by a protected level crossing allows vehicles to maintain their speed.
- Improving right-of-way: public transport lines that share the road with regular traffic will be held by congestion. Public transport on own lanes can drive at the road speed. Providing fully separated infrastructure allows vehicles to drive at higher speeds. Besides the direct effect of the increased driving speed, this measure also improves travel time reliability.
- Increasing line speed: In HiTrans (2005), it is noted that allowing vehicles to travel at higher speeds lowers their running times. This measure is most effective if vehicles can maintain this speed for some time and does not provide much benefit for short stop spacings and for vehicles with lower maximum speeds.

Reliability and experienced travel time

A low reliability of running times leads to additional travel time. Reliability can be improved by introducing slack in the driving times, which allows for minor disturbances during normal operations, although this leads to increased running times. Another possibility to improve service reliability is to decrease the variability of driving times. In section 2.2.1.1, it was found that there is always some variability in driving time, but the total variability adds up for each stop. Therefore, longer lines have a higher driving time variability. Splitting a long line into two shorter lines will increase travel time reliability (Figure 2-10) but impose an additional transfer for passengers. Choosing the right stop to split a line will result in an optimal solution between travel time losses due to variability and losses due to an additional transfer. Creating overlap in a core section reduces the required number of transfers and decreases travel time losses even more (van Oort & van Nes, 2009).

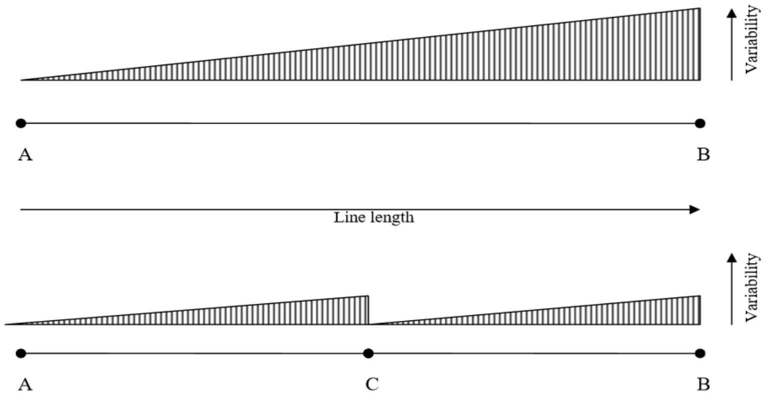


Figure 2-10: Effect of splitting a long line on travel time variability. Van Oort & Van Nes (2009).

Besides shortening the actual in-vehicle times, the attractiveness of public transport can also be improved by shortening the experienced in-vehicle time of passengers. The experienced in-vehicle time depends on the availability of seats and the crowding level of the vehicle. Increasing the number of seats improves the experienced travel time but decreases the capacity of vehicles.

2.2.2.4 Improving transfers

Although transfers are a necessity in providing effective public transport, they are also a hassle for passengers. The disutility of a transfer can be minimised by providing synchronised cross-platform transfers, as the walking and waiting time will be minimised (De Keizer & Hofker, 2013). Especially when frequencies are low, transfers should be synchronised. Here, travel time reliability plays a large role. When one of the two connecting vehicles is delayed, the transfer cannot be made. Therefore, in the timetabling of the two lines, some slack must be included. The slack directly influences the running time of the lines, and preferably is kept to a minimum. This is only possible if the punctuality is of sufficient level.

2.2.3 Attractivity and competitiveness: increasing network coverage

Network coverage is about the accessibility of a public transport network. In grid networks the stop and line spacing determine the maximum distance one has to walk to a stop. The accessibility can be improved by decreasing the stop spacing, but a downside of this measure is the resulting reduction in operational speed (Vuchic, 2005).

Public transport users outside cities typically rely on bus, car or bike transport to heavy rail stations and use the train to travel towards the city (KiM, 2017). Towns generally have one station, which cannot always cover a full town due to the maximum time people spend travelling. Adding an additional station improves the accessibility to some people, at the expense of an increased travel time for others.

Van der Blij, Veger & Slebos (2010) found that in The Netherlands, the catchment area for regular bus stops is around 450 meters, which would mostly be passengers walking to the stop. For high-quality public transport stops, the range increases to 800m. Ranges up to 1150m are realistic when cycling is commonly used as access mode, next to walking. Cycling commuters are even willing to travel 2.8 km to a high-quality stop. This is supported by a study of Brand et al. (2017), who found that for high-quality services, the share of bikes on the access side of trips increased.

Most cities only have a few heavy rail stations, and these are often located outside the city centre. For destinations close to stations, walking is the main egress mode, but for destinations further from stations, passengers have to transfer to lower-level (e.g. tram) public transport to reach their final destination. Brand et al. (2017) note that bike-sharing can play an important role in providing efficient egress modes for public transport. However, concentrating the transfer to bikes only at heavy rail stations leads to large footprints for storage areas (Van der Bijl, 2018). Therefore, in metropolitan areas it remains of great importance to provide adequate urban public transport beyond main stations. When cycling facilities are concentrated around metro stations or high-demand tram/bus stops, smaller storage areas will suffice.

It should be noted that cycling is common in Dutch culture, which means the effect of high-quality public transport and catchment area can be smaller in other places. If cycling is not expected to be a common access mode (e.g. in mountainous areas) or when accessibility must also be provided to people with reduced mobility (PRM), decreasing stop spacing and providing efficient access modes (e.g. regional buses of DRT) can improve coverage in regional areas.

2.2.4 Environment: stimulate light electrical rail transport

Electrical public transport is zero emission, at least at location of operation. Using green power strengthens the sustainability even more. For instance, the Dutch Railways operate for 100 per cent on wind energy, so travelling by train is fully climate neutral (NS, 2018). Governments play a large role in improving the sustainability of public transport by demanding that operators provide emission-free vehicles.

Because of improved batteries and faster charging technologies, the range (and thus operational possibilities) of electric buses is increasing (Wiercx et al., 2019). What used to be a large beneficial factor of rail transport, now also holds for buses. However, it has been noted that the environmental benefits of using electrical rail-bound vehicles in cities reaches further than just exhaust gas emissions. Besides exhaust gases, tyre and brake wear pay a large contribution to PM_{10} emissions (Thorpe & Harrison, (2008); Kruszelnicki (2012)). Modern trams can use regenerative (electrical) braking, saving both on energy usage and particulate emissions. Furthermore, rail transport is more energy efficient than buses due to the low friction of steel wheels and rails (Kay et al., 2011). Gibson et al. (2011) note that electrical rail is more efficient than diesel powered rail, and Kay et al. (2011) mention that reducing vehicle weight provides additional energy savings. Electrifying diesel lines and using light vehicles can improve the environmental quality in cities and reduce the energy consumption of the transport system.

2.2.5 Attractivity and comfort: improve passenger experience

Figure 2-2, as developed by Peek and Van Hagen (2002) shows satisfiers and dissatisfiers in public transport. Improving travel speed and convenience (transfers) were discussed in section 2.2.2. Convenience can also be improved by ensuring good accessibility and facilities for cyclists (Leferink, 2017). Increasing the level of the satisfiers, comfort and experience, can increase the quality of the offered service. Comfort can be increased by, amongst others, providing modern, clean vehicles and sheltered waiting areas (Redman et al., 2013). From Wardman & Wehlan (2010), it was found that crowded vehicles negatively influence passenger experience. Providing enough seating space in trains increases comfort for passengers. However, it should be noted that providing more seating space limits the total capacity of a vehicle, which might need to be compensated for. The ‘railbonus’, as researched by Bunschoten et al. (2013) shows that passengers experience rail-bound modes over buses.

2.3 Conclusion

In this chapter, the three main stakeholders in public transport have been discussed; passengers, operators and governments. For each of the stakeholders, the main objectives for public transport were identified. These objectives were translated into specific measures that can be taken to improve public transport usage. Five measures were described: increasing line capacity, decreasing travel time, increasing network coverage, stimulating light electrical rail transport and improving service quality.

Increasing frequency of services improves both travel time and line capacity, while stop spacing is a trade-off between accessibility (and access time) and running time. Decreasing stop spacing can mean an improved accessibility for some people, while the total travel time for others is increased because of extra stops. High-quality public transport stops, combined with good cycling facilities can increase the catchment area of such stops a lot, easing access to public transport in a region.

3 Public transport in urban regions

This chapter describes the supply side of public transport systems in urban regions. By supplying adequate public transport, the demands discussed in the previous chapter can be met. Supply of public transport consists of several modes, each with its strengths and weaknesses. Based on system parameters, the characteristics and the strengths and weaknesses of the most common modes in public transport are described.

Public transport comes in many forms and sizes, all with the aim of transporting many people with (a set of) vehicles. However, the characteristics of the various modes differ a lot. Some types of public transport are very flexible and accessible, while others require own infrastructure with large stations. There are cities with public transport networks that include all modes, but some cities only rely on buses.

3.1 System parameters

Public transport systems can be distinguished and classified by determining certain system parameters. These parameters will be used to compare the various modes. Three sets of system parameters are used:

1. Operational parameters (Table 1-1).
2. Technical parameters related to the vehicle (Table 3-1).
3. Technical parameters related to the infrastructure (Table 3-2), which describe the technical details of the infrastructure. These are mostly applicable for rail-bound modes.

The operational parameters of a system follow from the technical parameters. The technical parameters define what a system can and cannot do. Certain desired operational parameters cannot be provided by all systems. For instance, rail-bound systems cannot achieve high maximum speeds at very short headways, as the long braking distances prohibit this.

Table 3-1: Technical parameters related to vehicles.

Parameter	Unit	Description
Maximum speed	km/h	The maximum speed a vehicle can reach.
Vehicle length	m	The length of a vehicle.
Vehicle width	m	The width of a vehicle.
Axle load	t	The load that each axle bears.
Vehicle capacity	pass.	The number of people that fit in one vehicle, at a crush density of 4 passengers/m^2.
Power supply	V	The source of energy for traction, including voltage for electrical vehicles.
Crashworthiness	kN	The minimum compression load of a rail vehicle, according to norm EN12663-1.
Floor height	mm	The height of the vehicle floor above the top of the rails.
Minimum curve radius	m	The smallest curve a vehicle can safely negotiate.
Acceleration / (emergency) deceleration	m/s^2	The maximum acceleration and deceleration a vehicle can achieve.

Table 3-2: Technical parameters related to infrastructure.

Parameter	Unit	Description
Track gauge	mm	The width of railway track.
Rail type	--	The type of railhead that is used; grooved or Vignole ('standard') rail.
Platform height	mm	The height of platforms above the top of the rails.
Driving regime	--	Whether vehicles drive on sight (no technical protection) or supervised/protected via (cab) signalling. Mostly relevant for rail-bound modes.
Overhead line height	m	The height of overhead lines above the top of the rails.
Points control	--	How railway points are controlled (from the vehicle or via interlocking and traffic control).

3.2 Public transport modes

Bus systems are the lowest level of public transport, and due to the low cost and flexibility, there are almost no cities in which no bus system is used. If the capacity of a normal bus line is insufficient, trams can be used. As trams can share the road with regular traffic, upgrading a bus line to a tram line does not need to lead to large modifications to street layouts. The larger vehicles can transport more people without the need to increase frequency. Van der Bijl et al. (2015) note that a line headway of 5 minutes is the minimum from a quality perspective, with smaller headways possibly resulting in bunching.

On shared corridors, headways between vehicles from different lines can be smaller, although congestion becomes a threat for reliable operations. In these cases, separating the public transport infrastructure from regular road infrastructure is required (ROW B). Tramways can be built in grass lanes, having a greener appearance than additional asphalt for busways. On the other hand, paved public transit lines can also be used by emergency vehicles (Donders, 2018). On the separate infrastructure, in combination with priority at intersections, headways can be decreased which increases the capacity.

A further capacity increase can be achieved by fully segregating the infrastructure from the road network on busy corridors (e.g. in a tunnel or on a viaduct), while maintaining surface level running on other sections (ROW B/C). For instance, in The Hague, NL, a tram tunnel has been constructed underneath the city centre. On other parts of the network, trams run on separated tramways and on streets.

The highest level public transport system within a city is the metro system, which is fully separated from other infrastructure and built to transport many passengers over relatively short distances. Vehicles are longer and wider than trams and run on headways as short as 90 seconds. Peak capacities of 75000 passengers per hour per direction can be achieved. The fully closed infrastructure causes expansions of metro systems to be very expensive. Due to the high costs, metro systems are useful from agglomerations of over 1 million inhabitants. Smaller agglomerations do not have sufficient transport demand to justify a metro system (Metrobits, 2018).

An additional level of public transport serves urban regions: the heavy rail network. Regional trains or S-bahn systems run from main city stations to outskirts and neighbouring towns. Lines are longer than those of metros and as stops are farther apart, trains can run at high speeds between the stations. In many cities, regional railways cross city centres in tunnels, sometimes with several lines bundled. The difference between the city-oriented metro system and region-oriented S-bahn is shown in Figure 3-1.

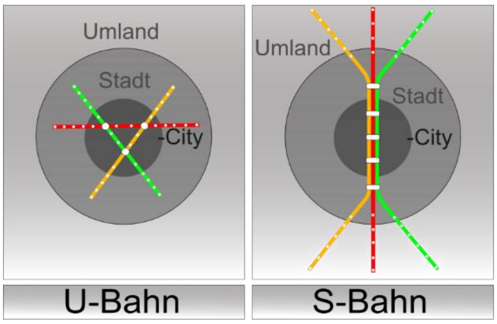


Figure 3-1: Difference between metro (U-bahn) and regional train (S-bahn). Wikipedia (2018).

The highest levels of public transport are the intercity and high-speed rail networks. These are focussed on transporting many passengers over long distances at high speeds. Often, cities only have one (central) or two stations as access nodes to the intercity network.

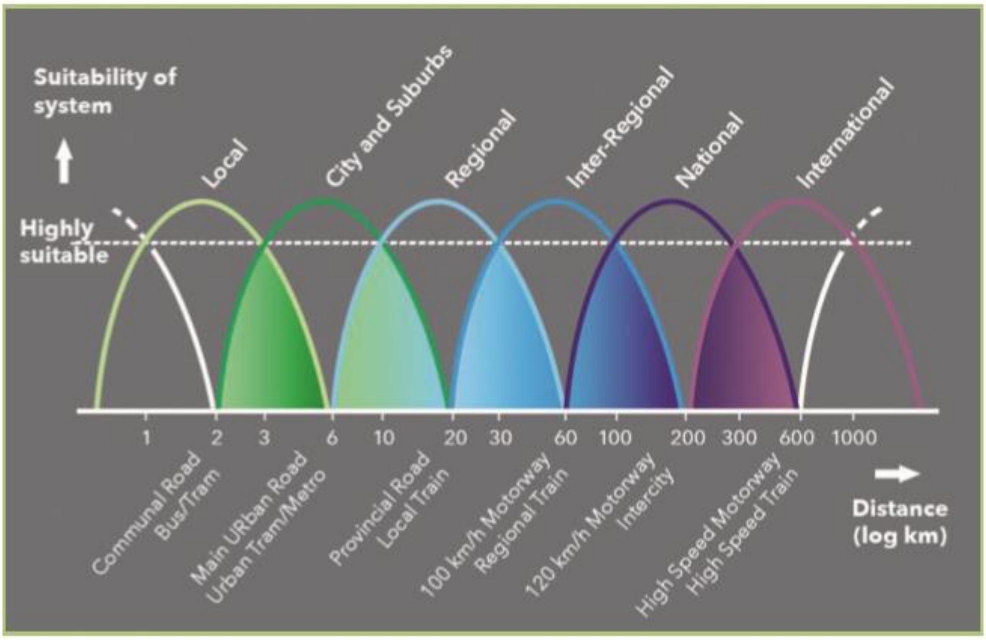


Figure 3-2: Spatial scale of modes. Goudappel Coffeng (n.d.).

Table 3-3 through Table 3-5 summarise the main operational and technical parameters of the described systems. The values can be interpreted by plotting parameters against each other. Figure 3-2 shows the suitability of modes for certain distances. Modes with lower operational speeds have shorter lines and are operated on smaller spatial scales. Figure 3-3 illustrates the relationship between operational speed, maximum speed and stop spacing. Typical ranges for various modes are shown, with the operational speed based on an acceleration and deceleration of 1.0 m/s^2 and a dwell time of 20 seconds (HiTrans, 2005).

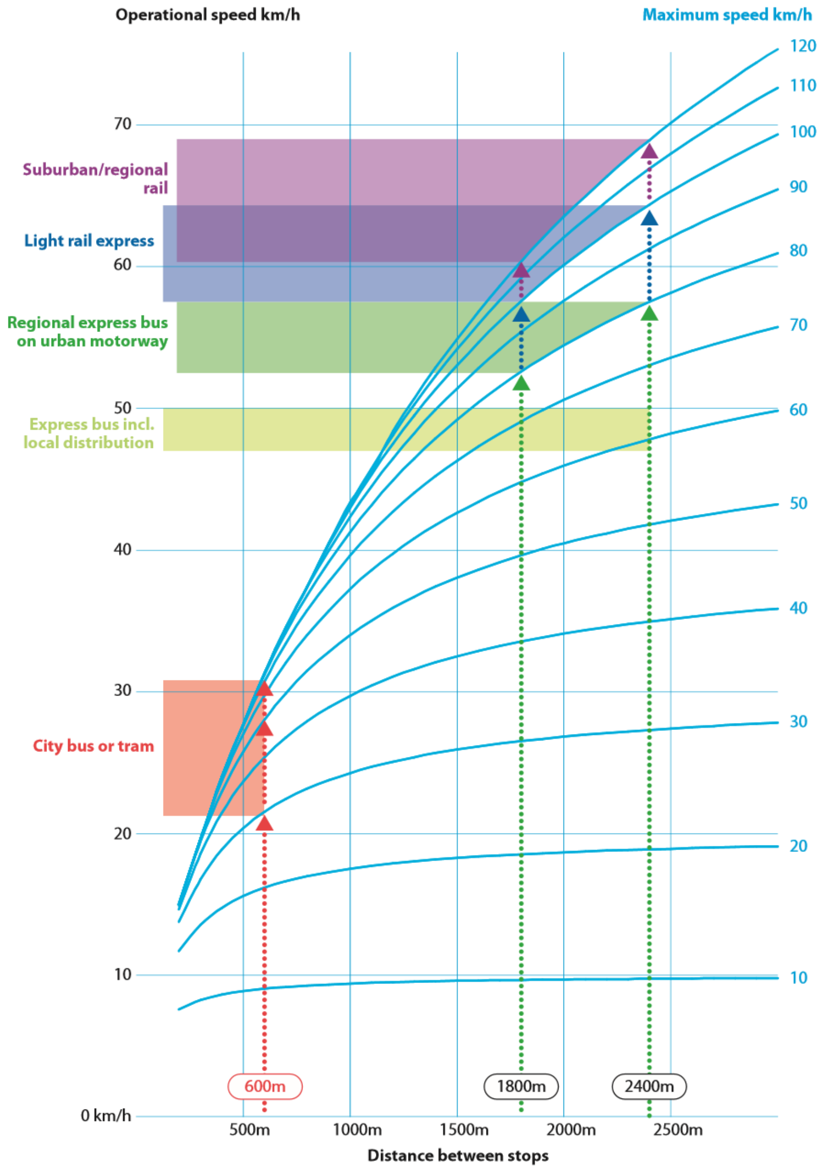


Figure 3-3: Relation between maximum speed, operational speed and stop spacing. HiTrans (2005).

Table 3-3: Summary of operational parameters.

	Bus	BRT	Urban Tram	Regional Tram	Metro	Regional Train	Intercity
Average speed	15 - 20 km/h	20 – 40 km/h	15 km/h	30 – 45 km/h	30 km/h	> 60 km/h	> 80 km/h
Stop spacing	200 – 500 m	300 – 2000 m	200 – 600 m	0.4 – 2 km	0.4 – 1.6 km	2 – 5 km	> 10 km
Dwell time	10 s – 1 min	10 s – 1 min	< 30 s	< 30 s	< 30 s	1 min	3 min
Line length	--	--	5 – 20 km	10 – 40 km	5 – 30 km	> 20 km	> 50 km
Network structure	Grid / Radial	Radial / Tangential	Radial as backbone. Grid as feeder service.	Radial	Radial / Tangential	Radial	City-to-city
Peak capacity	1200 pphpd	36000 pphpd	5000 pphpd	14000 pphpd	75000 pphpd	--	--

	Bus	BRT	Urban Tram	Regional Tram	Metro	Regional Train	Intercity
Minimum headway	5 min / line	13s	5 min / line	3 min / line	1.5 min	2.5 min	2.5 min
Degree of separation in traffic	ROW C	ROW B/C	ROW B/C	ROW A/B	ROW A	ROW A	ROW A
Integration in city	Well integrated	Moderately integrated	Well integrated	Moderately integrated	Closed	Separated	Separated

Source: Appendix A

Table 3-4: Summary of technical parameters – Rolling Stock.

	Bus	BRT	Urban Tram	Regional Tram	Metro	Regional Train	Intercity
Maximum speed	80 km/h	80 - 100 km/h	< 70 km/h	<80 km/h	80 km/h	> 100 km/h	> 100 km/h
Vehicle length	12 m	18 m	< 35 m	25 – 75 m	50 – 150 m	50 – 200 m	> 100 m
Vehicle width	< 260 cm	< 260 cm	220 – 265 cm	< 265 cm	220 – 300 cm	< 315 cm	< 315 cm
Vehicle weight / axle load	11 t	16 t	< 11.5 t	<11.5 t	<17.5 t	< 21 t	< 25 t
Vehicle capacity	< 100 passengers	< 180 passengers	< 250 passengers	< 700 passengers	< 2000 passengers	< 1500 passengers	< 2000 passengers
Power supply	Diesel / battery	Diesel / battery	600 / 750 V Overhead lines Battery (short distances)	600 / 750 V Overhead lines	750 V, 3rd rail	> 1.5kV Overhead lines Diesel	> 1.5kV Overhead lines Diesel
Crash-worthiness	n.a.	n.a.	> 200 kN	> 400 kN	> 800 kN	> 1500 kN	> 1500 kN
Floor height	190 - 300 mm	190 – 300 mm	350 mm	350 mm	> 750 mm	> 760 mm	> 760 mm
Minimum curve radius	18 m	24 m	20 m	20 m	> 120 m	> 180 m	> 180 m
Acceleration / (emergency) deceleration	--	--	1.3 / (> 2.5) 1.2 m/s^2	1.3 / (> 2.5) 1.2 m/s^2	1.0 / 1.15 m/s^2	0.6 – 1.0 / 0.8 – 1.2 m/s^2	0.6 – 1.0 / 0.8 – 1.2 m/s^2

Source: Appendix A

Table 3-5: Summary of technical parameters – Infrastructure.

	Bus	BRT	Urban Tram	Regional Tram	Metro	Regional Train	Intercity
Track gauge	n.a.	n.a.	1000 / 1435 mm	1435 mm	1435 mm	1435 mm	1435 mm
Rail type	n.a.	n.a.	Grooved	Grooved / Vignole	Vignole	Vignole	Vignole
Platform height	180 mm	180 mm	300 mm	300 mm	Level with floor	550 / 760 mm	550 / 760 mm
Driving regime	On sight	On sight	On sight	On sight / protected	Protected	Protected	Protected
Overhead line height	n.a.	n.a.	> 4.7 m	> 4.7 m	n.a. (third rail)	5.5 m	5.5 m
Points control	n.a.	n.a.	From vehicle	From vehicle / via interlocking	Via interlocking	Via interlocking	Via interlocking

Source: Appendix A

3.2.1.1 Cost comparison

Figure 3-4 shows the investment costs per kilometre of new line for busways, BRT, LRT (light rail) and metro, plotted against transport capacity. The figure shows that rail systems are more expensive than bus systems, which is due to the additional required infrastructure. Although metro systems are the most expensive to build, they also have the largest potential capacity. Additionally, operation of a metro system is as expensive as a BRT system at low transport demands, but gradually becomes much cheaper as demand grows (UN-Habitat, 2013).

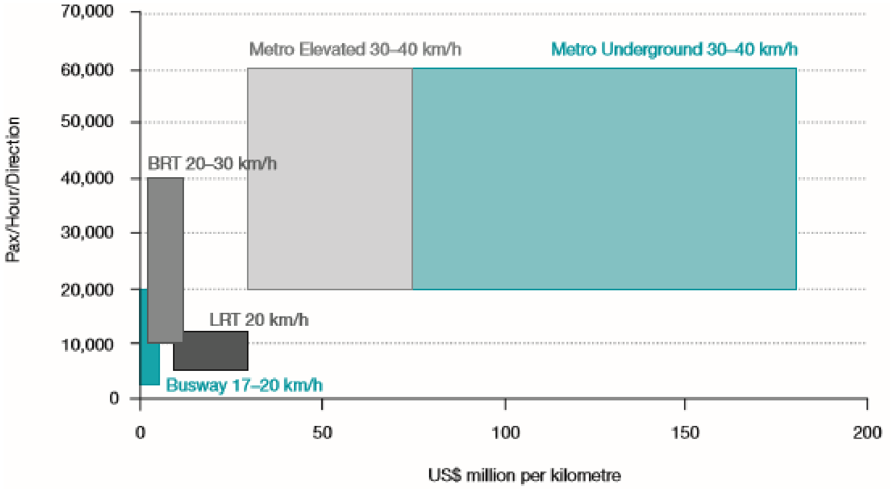


Figure 3-4: Initial cost versus capacity and speed. UN-Habitat (2013).

3.2.1.2 Technical design versus operational characteristics

Although some systems are technically a certain mode, their operations can be classified as a lower (or higher) level mode. The Parisian underground networks illustrate this. The metro of Paris has a stop spacing of 500-600 metres on many lines in the city centre, which leads to an operational speed of 20 km/h, similar to many tramways. As a result, the Parisian metro is too slow to provide public transport to the suburbs, which is why the RER (Réseau Express Régional, regional trains) was built. The RER has metro-like operation in central Paris, with very short headways and stop spacings of more than a kilometre, but it is technically a heavy railway.

3.2.2 Typical urban public transport networks

In metropolitan areas, combinations of public transport modes are used to provide hierarchical transport networks. In large cities, metro transport provides the backbone of public transport in the city (Amsterdam, London, etc), while heavy rail is the main transport mode outside the city. Regional public transport towards a city is often strengthened by small hubs where rural bus lines connect to the trains. In cities, buses and tramways are used as a feeder system towards the heavy rail and metro networks (TRB, 2013). In smaller cities, tramways can be used as main public transport in the city centre, while buses connect the suburbs.

Park & Ride

Cities can provide park & ride facilities, at edges of the city and with good motorway connections. At these locations, large parking facilities are combined with fast public transport towards city centres. Travellers are persuaded to park at these facilities and continue their journey by public transport, to reduce car traffic in city centres. Therefore, parking at park & ride is free-of-charge or combined parking and public transport tickets exist, at attractive fares (HiTrans, 2005).

3.2.3 Alternative modes

Above, the ‘traditional’ modes have been described. However, in some cities, other forms of public transport are applied. In several South-American cities, cable cars are used for public transport. Advantages of cable cars include the ability of overcoming large height differences and the little required space (The Economist, 2017).

In several airports and some cities (e.g. Rotterdam), automated vehicles are operated on separated tracks, often without interfaces with other infrastructure. In Rotterdam, group rapid transit (GRT) vehicles are fully automated and run on their own tracks, with level crossing-like intersections with regular traffic. An extension is planned towards a nearby waterbus stop, with a section on public roads. After the extension, the system provides a quick connection between the waterbus and metro of Rotterdam. The system can transport up to 500 passengers per hour, with an optimal headway of 4 minutes, and is used as egress mode for the metro. Outside peak hours, the operator can select whether the system operates on-demand (2getthere, 2018).

Emerging modes

Autonomous vehicles have taken a flight over the last years, and several companies, both car manufacturers and service companies (such as Uber and Google) are experimenting with driverless vehicles. Simultaneously, experiments have been going on with small-scale autonomous public transport on public roads (WePods, TU Delft & Wageningen). While these pilot projects have ended, similar systems may become an addition to the current public transport modes. Such small vehicles can for instance be used as access and egress mode, collecting people on demand and bringing them to a station.

Another emerging mode is demand responsive transit (DRT): Passengers reserve a small vehicle, operated by a public transport company, which picks them up at a bus stop and transports them to another stop (Breng, n.d.). These flexible services allow operators to use small vehicles more efficiently, compared to standard buses with only a few occupants.

3.3 Conclusion

In this chapter, the most common modes of public transportation in urban regions have been discussed. It was shown that bus systems are cheaper to build and more flexible than rail systems, but rail systems can transport larger numbers of people and are generally faster. Access and egress facilities such as park & ride, DRT and bike sharing can improve the accessibility of a public transport system and increase the network coverage.

4 Tram-Train

In the previous chapter, various modes of public transport were described. In this chapter, the concept of tram-train is introduced. Tram-train is a combination of two modes, and if implemented properly, can use the strengths (such as the accessibility of a tram and high speed of a train) of both tram and heavy rail systems to overcome weaknesses (such as the limited penetration into cities of trains and low speed of trams) of either system. A classification of tram-train systems is presented, which is illustrated by several reference systems. From these examples, the system parameters are determined. Furthermore, advantages and disadvantages of tram-train schemes are given, as well as the type of city and urban region tram-train is suitable for.

4.1 What is tram-train

Generally, different rail-bound public transport modes are kept strictly separated. However, this means that transfers from regional railway lines to urban public transport in city centres are a necessity. Commuter towns often only have one or two heavy rail stations, with some (low frequency) bus lines as access mode. Therefore, for many people the attractiveness of public transport is too low to be a real alternative to car commutes.

4.1.1 Karlsruhe model

In the late 1950’s, a regional railway in Karlsruhe (the Albtalbahn) suffered from low ridership, due to its main station being outside the city centre. It was decided to transform the narrow-gauge railway to a standard-gauge tramline and connect it to the existing network. Later, the tram network was further extended by new tramlines on separate tracks. By providing right-of-way at intersections, the speed of the trams became competitive to road transport. In the end of the 70’s, another heavy railway line was converted to a tram line. The new lines to neighbouring towns had good ridership, so there were ideas to extend the network. As all main railway stations were outside of the city centre, providing direct lines from outskirts to the centre would be beneficial for passengers. To extend the network cost-effectively, it was chosen to connect the tramway network to the rail network and share the tracks with regional and national trains. For this, vehicles had to be modified to operate under 750V DC of the tram network and 15kV AC of the main lines, but also be able to operate both as an urban tram (according to BOStrab – German tramway specification) and as a train (according to EBO – German guidelines for heavy rail operation). Moreover, the vehicles had to be strengthened to withstand a vehicle-vehicle collision with heavier trains. In September 1992, the first mixed line commenced operation: the *Karlsruhe model* for tram-train was born (Perez, 2004).

Figure 4-1: Start of EBO section. Note the small sign at the bottom.

However, integrating an urban or regional tram with a nationally orientated railway network requires cooperation of many parties, which directly is the main challenge of tram-train (Van der Bijl, 2018; Kats, 2018). Generally, there are operators of the tram- and train network (the latter might even be several), the infrastructure manager of the heavy rail network, a regional government or transit authority and a national government. In metropolitan areas where the various towns are not served by a single transit authority, it will also require coordination between the local governments. Figure 4-2 provides an overview of the stakeholders involved in a tram-train project. Each of the parties, and especially the private companies, has its own agenda and want to protect its own business.

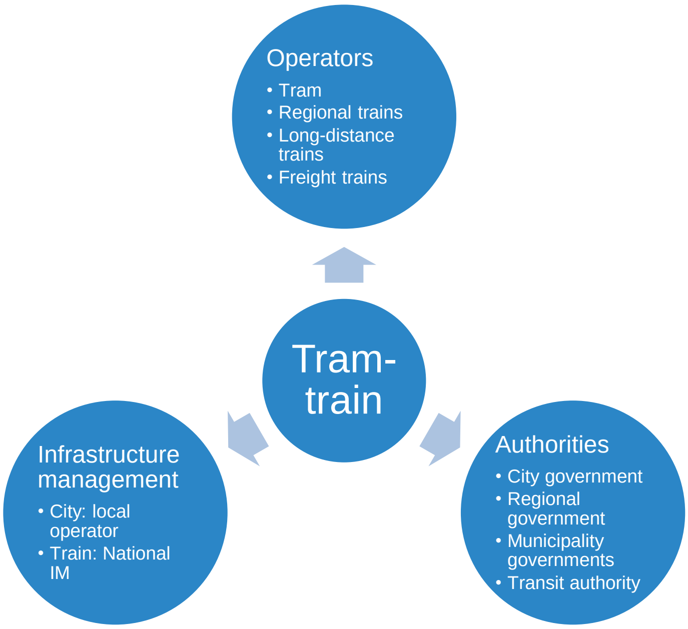


Figure 4-2: Stakeholders in a tram-train project.

4.1.2 Transformation of old railway lines

According to Van der Bijl et al. (2015), tram-train also includes systems which use tracks previously used for heavy rail, but on which heavy rail operations are discontinued. In these cases, there are no mixed operations of trams and trains. Platforms can be modified to suit the floor height of trams and trams only need to be modified to be able to run on heavy rail tracks. Maintaining typical features of heavy rail infrastructure, such as higher voltage overhead lines and train protection systems still requires dual-mode vehicles.

4.1.3 Operational concept

If implemented properly, tram-train can combine the advantages of both modes, while overcoming several disadvantages. Van Oort and Weeda (2007) describe the operational differences between train and tram and indicate the strengths of both systems. They note that learning from each other’s practice, the service level of both tram and train can be improved. While train timetables are designed on theoretical values and built to be reliable, tram operators focus on operational speed and base their timetable on achieved running times. Van Oort and Weeda (2007) also discuss that both speed and reliability are important but should be captured in the actual travel time for the traveller. Similarly, for timetabling, using both theoretical running times and feedback from practice could lead to a more ideal timetable.

Within cities and towns, tram-train benefits from the accessibility of short stop spacing and can bring passengers very close to where they want to go. On the main lines between cities, tram-trains benefit from the right-of-way of the tracks and high speeds that can be achieved.

4.1.4 Classification of tram-train systems

Naegeli et al. (2012) present a clear classification scheme for tram-train systems. They classify systems on whether shared running is applied on heavy rail and/or urban tracks. Four categories were identified, although for their research it sufficed to combine systems without shared operations on train tracks into one class (class C). For this thesis, the fourth class is distinguished as well, although most attention is given to class A and B systems. A classification of tram-train systems, indicating the Karlsruhe model is given in Figure 4-3.

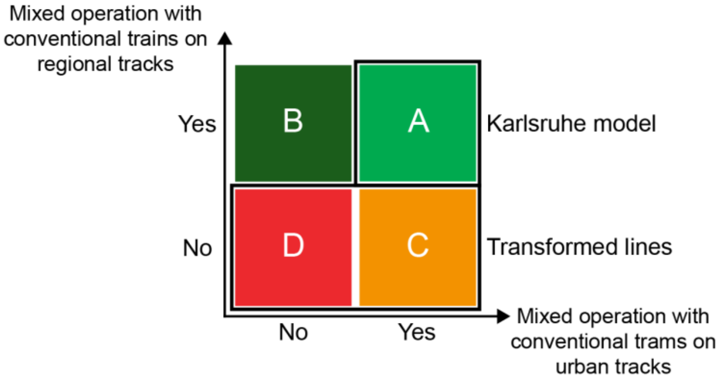


Figure 4-3: Classification of tram-train models and systems. Adapted from Naegeli et al. (2012).

4.1.5 Train-tram: Zwickau model

The Karlsruhe concept can also be reversed, as a train-tram system. In this case, heavy rail trains continue into the city centre along urban tram alignments. This scheme is very uncommon, due to the characteristics of heavy rail vehicles. As the trains have a width of 2.95m, they are much wider than the BOStrab allows (2.65m). Therefore, the vehicles are not allowed to operate as a road vehicle, and intersections are treated as level crossings (Karr, 2018). Figure 4-4 shows a train-tram on ROW B dual gauge alignment in Zwickau.

Figure 4-4: Train-tram on the Zwickau tram network. Also note the dual gauge.

4.2 State-of-the-art

For each class of tram-train, a few existing systems are described. In networks, it is possible that one of the lines is of a different class, which is indicated. Selection of the systems initially focused on class A and B systems and Dutch examples. For each of the analysed systems, remarkable features of that specific system are noted. Furthermore, two proposed tram-train projects that were not implemented and future vehicle developments are discussed.

Appendix C.1 lists the population figures of the analysed cities and served regions.

4.2.1 Class A

Class A systems are based on the Karlsruhe model. The experience and regulations gained in Karlsruhe aided in successful implementation of class A systems mainly in other German cities, but the concept has spread to other countries as well.

4.2.1.1 Karlsruhe Stadtbahn (network, also class C)

The German city of Karlsruhe was the first to construct a tram-train network. Over the years it has expanded into a vast network of regional lines that run directly into the city centre of Karlsruhe. In Wörth, Heilbronn and Bad Wildbad, tramway tracks were constructed to provide direct access from the town centres to regional transport (AVG, 2015). Some lines have lengths of more than 80 kilometres, and the vehicles operated on these lines even feature toilets, which take up vehicle space and add to the price of the vehicles.

As the tram-train shares the tracks with a heavily used train network, some lines only have a few slots per hour, which results in low frequencies. To provide additional capacity, these lines are run with coupled vehicles (double traction). These 75m vehicles (the maximum as regulated by BOStrab, the German tramway regulations) continue their journey through the city centre. Some tram lines are also run in double traction. In pedestrian areas, the combination of many long vehicles and high frequencies can be a hindrance or even dangerous for roaming pedestrians (Djoko, 2018).

The vehicles are designed to automatically change between the 750V DC voltage of the tram network and the 15kV AC of the train network. The changeover areas between the BOStrab and EBO are marked with small signs (Figure 4-1).

The first series of vehicles had high floors, which caused poor accessibility for people with reduced mobility. As heavy rail stations in Germany have platform heights of 55 centimetres, it was chosen to build medium-floor vehicles rather than low-floor vehicles. As a result, accessibility from regular tram stops (height of 34 cm) is still not provided. In the city network, some stops have platforms at both 34 and 55 cm but a length of 150 meters. In some stops, a raised platform to serve the first two doors is provided, which reduces the required stop length significantly. However, this solution cannot serve both vehicles in a double-traction train.

Future of the Karlsruhe network

The combination of the successful tram-train scheme with a heavily used tram corridor caused the municipality of Karlsruhe decide to build a tunnel underneath a part of the city centre. It is hoped that this will improve the service reliability on the section. Moreover, some of the long tram-train lines will be shortened and replaced by regional trains with zonal operation (see section 2.2.2.3). A regional train will take over the local services on the regional stretch and operate as express service between the tram-train terminus and Karlsruhe (Kühn, 2018).

4.2.1.2 Kassel RegioTram (network)

After the success story of Karlsruhe, the transit authority of Northern Hesse (NVV) studied the possibilities of connecting the heavy rail network of Deutsche Bahn to the local tram network. A newly opened rail station (Wilhelmshöhe) had become Kassel's main station in the national railway network, leaving the more centrally located Hauptbahnhof merely as a terminus for local lines. Therefore, connecting the tram network with the regional rail network through the Hauptbahnhof closes the gap between the two networks (NVV, 2006).

The connection was made by building a short tunnel underneath the main station building and linking to the street network directly afterwards. In the station, two platforms were built in the deepened section. Using the main station as entry into the tram network enables combined operations: double vehicles on the regional section, which are separated into two different urban tramlines at the main station.

A regional line that was connected to the RegioTram network, could not be electrified due to an old, low tunnel (modification cost: €7.5m (Streeter, 2010)). Therefore, it was decided to design tram-train vehicles that run on 600V overhead power within the city centre and rely on diesel traction on the unelectrified regional line. For the other, electrified, train lines bi-current vehicles were bought. Both sets of vehicles are Alstom RegioCitadis, and technically, the bi-current 600V DC / 15kV AC and dual-mode 600V / diesel vehicles are the same, except for parts of the electrical equipment and diesel engine (NVV, 2006).

With the inauguration of the RegioTram, several existing stops were modernised, and new stops could be opened, without adding additional travel time (Streeter, 2010). Besides, the regional train services could be sped up, as stops previously served by trains were now served by the RegioTram (NVV, 2006).

Usage of the lines has increased tremendously. Between 2008 and 2015, ridership increased from 3.1 to 5.8 million passengers (+87%), with RT4 increasing from 490000 to 2 million passengers in 8 years (NVV, 2016).

Tram 4, between Kassel and Hessisch-Lichtenau shares part of its alignment with freight trains. As the trams of Kassel are 2.40m wide, stops had to be built outside the clearance gauge of the freight trains. Therefore, some stops are on a short side track next to the railway, while in others, there are small stretches of gauntlet track next to one of the platforms. For a stop along single-track alignment, this resulted in 6-rail tracks, as shown in Figure 4-5. The tram vehicles may be operated on these regional railways, but not on the main lines (Bundeslinien).

Figure 4-5: 6-rail track at Hessisch-Lichtenau. Axel Kühn.

4.2.1.3 Chemnitz CityBahn (network, also class C)

In Chemnitz, the first tram-train pilot route (C11) was opened in 2002. The route consists of a single-track stretch between Stollberg and Altchemnitz, which was rebuilt for tram-train operation and the heavy rail operation was suspended. The section was electrified at 750V DC for the project, while the existing tram network of Chemnitz is operated at 600V DC. After completion of the pilot project, ridership grew to 5000 daily passengers, greatly exceeding the expected 2500 daily users. The network is still under expansion, as several surrounding towns are being connected, with lines C13, C14 and C15 sharing tracks with regional trains. The tram network has also been extended towards the university. New hybrid (diesel / electric 600V) Stadler Citylink vehicles have been acquired to operate the lines. Although some heavy rail lines are electrified at 15kV AC, the vehicles cannot use this power supply (VMS, n.d.). As one of the lines is not electrified, the decision might have been to procure one type of vehicle, rather than was done in Kassel.

On the heavy rail sections, the average stop spacing is quite large with generally one stop in each town. As a result, overall average speeds are relatively high. Remarkable for the Chemnitz network is the solution to different platform heights. The tram network has platforms of 200 and 380mm a.t.r., while the main line platforms are at 550mm a.t.r. The vehicles are equipped with four doors on each side, two of which have an entrance height of 405mm. The other two doors have an entrance height of 570mm. In the vehicle are small ramps. The vehicle features extendable steps to allow for usage of all doors (Stadler, n.d.).

Figure 4-6: Citylink Chemnitz. The entry height difference between the white and red door is clearly visible. M.Bearton/Railwaymedia.

4.2.1.4 Nordhausen (single line)

In the German city of Nordhausen, the metre-gauge tramway is connected to the narrow-gauge tracks of the Harzer Schmalspurbahn. As the tracks of the Harzer Schmalspurbahn are not electrified, hybrid diesel-electric vehicles (Siemens Combino Duo) are used. The train tracks are shared with some other passenger (steam!) and freight services. Remarkable for Nordhausen is its small size. With only 44,000 residents, the city has a network of two tram lines. The villages served by the hourly tram-train have just over 6000 inhabitants in total.

4.2.1.5 Tram-train Mulhouse Vallée de la Thur (single line)

In Mulhouse, France, a tram network of 4 lines exists. One of the lines is connected to the heavy rail network of SNCF at Lutterbach. The connection consists of 3.7 kilometres of ROW A alignment alongside the main line Mulhouse - Strasbourg, which branches off at Lutterbach. From there, it is operated as a tram-train towards Thann, sharing the tracks with SNCF trains. On the tram network, the Siemens Avanto vehicles are powered by 750V DC from the overhead lines and switch to 25kV AC on the train line, which was electrified for the tram-train. With a daily ridership of 8000 passengers, the system is not performing as hoped (Kühn, 2018).

4.2.1.6 Sheffield – Rotherham tram-train (single line)

The Sheffield – Rotherham tram-train is an extension to the Sheffield Supertram network. It is a pilot project with tram-train in England, to see whether the scheme can be used in other parts of the country as well. Infrastructural modifications included electrification of the heavy rail section (at 750V DC for now, but structurally prepared for 25kV AC) to Rotherham and construction of a connection chord of 150 meters. Electrification at 25 kV AC proved too costly for the short section but can be upgraded in the future when adjacent main lines are electrified as well (Taut, 2017).

The tram-train will run from the city centre of Sheffield towards Rotherham Parkgate shopping centre, partly along tram and partly along train alignment. With the new service, it will be possible to travel from Rotherham directly into the centre of Sheffield.

4.2.2 Class B

In class B systems, there is no shared operation on a tram network, for instance due to the absence of a tram network prior to the implementation of tram-train. The tram section can be designed specifically for tram-train, to overcome technical integration issues. When a tram network is present, the tram-train can still be operated separately from this network. Kühn (2018) notes that this is a French approach to tram-train, where the national railways (SNCF) operate the tram-train as service improvement to old regional trains.

4.2.2.1 Tram-train Nantes (network, also class D)

The French city of Nantes has a small tram network, and two tram-train lines, although the tram-train lines are separated from the tram network. One line runs from Nantes to Clisson over heavy rail tracks, which are also used by regional, intercity, high-speed and freight trains (thus Class B). The tram-train serves several stations along the line. At Clisson, it is possible to transfer to regional trains, which do not serve the intermediate stops (SNCF, 2018). The second line, from Nantes to Châteaubriant has a length of 64 km and serves 11 stations. In Nantes, it shares its alignment with the tram, but has its own tracks. The tram-train line has one station, where the adjacent tram line has several stops. The line is separated from the remainder of the former Nantes – Rennes train line in Châteaubriant, and not served by other trains. This makes it a Class D line, and except for the ROW B alignment, it is basically a train line. In the urban area, the line is powered at 750V DC and the regional section is powered at 25kV AC (Railwaygazette, 2014). Not all services on the line continue to Châteaubriant. Several services short-turn in Suce-sur-Erdre or Nort-sur-Erdre, while only eight trains per day are operated between Nantes and Châteaubriant (SNCF, 2018a).

4.2.2.2 Hoekse Lijn (single line)

The Hoekse Lijn is a former Dutch heavy railway line that has been converted to a metro line and connected to the existing metro network of Rotterdam. Infrastructure and operations have been transferred from ProRail (IM) and NS (TOC) to the RET, the local metro operator. Some adjacent industries required to remain accessible by freight train, and therefore, a small section (± 3km) can still be used by freight trains. Although not a tram-train line (conversion to metro-train), the combination of metro and freight trains can be classified as Class B and provides relevant technical information for tram-train. A main technical issue on the shared section is the difference in vehicle width, which is analysed for usage in the technical integration library. No analysis on system parameters and city characteristics is done.

4.2.2.3 Cádiz (single line)

Cádiz, located on a narrow peninsula, has an existing heavy railway connection to the rest of Spain. To improve connectivity to two neighbouring cities, a tram-train line towards San Fernando and Chiclana de Frontera has been built. Between Cádiz and San Fernando, there is shared running on heavy rail tracks for 10.3 km. At San Fernando, the tram-train line branches off the mainline and runs through San Fernando, towards Chiclana de Frontera. The tram section consists of 8 km of interurban (ROW B) track and 5.5 km of urban track (ROW C, including gauntlet track sections). A typicality of the Cádiz system is the usage of Iberian gauge (1667 mm) tracks, but the sleepers are prepared for a future changeover to standard gauge.

Of the 300,000 residents in the served cities, 230,000 live within a kilometre of a stop (75%), showing the accessibility of a tram-train system. When the full line is operative, a yearly ridership of over 6 million passengers is expected (Novales & Conles, 2012).

4.2.2.4 Cardiff (single line)

In Cardiff, Wales, the Welsh department for Transport has decided to take over most infrastructure from Network Rail, the IM in the UK, and put up the entire rail service as a competitive tendering procurement. The winning bid was a scheme of regional lines served by trains on lines shared with freight traffic, and tram-trains on lines that do not, or only for short sections, share tracks with freight trains (Briggs, 2018).

To improve the service, the lines will be electrified at 25kV AC, which is the same as the rest of the British heavy rail network. Stadler Citylink dual-mode (25kV / battery) tram-train vehicles similar to those in Sheffield will be used, except that they have a high floor. Using the same vehicles as in Sheffield eases cooperation with Network Rail on the short shared-running sections. As the vehicles mostly serve existing stations and Cardiff does not have a tram network, using high-floor vehicles does not require modifications to platforms (Briggs, 2018).

The tram-train ability is used in a small new extension to the rail network near Cardiff Bay. From the heavy rail station, a short section of ROW B alignment is constructed towards Porth Teigr where several offices and nightlife are located. The extension features regular intersections with road traffic, with trams operated on sight. Extending the line as tram line was much cheaper than as a train line with level crossings and enables future expansions on street alignments (Briggs, 2018).

4.2.3 Class C

In class C systems, former railways are modified to be operated by tram-train vehicles. In some Class A systems, local railways were transformed into Class C lines. Class C tram-train can easily be confused with regional tram lines (generally referred to as light rail), but the distinction is the operational principle, which is according to heavy rail regulations.

4.2.3.1 RandstadRail (network)

The region around The Hague – Rotterdam used to have two commuter rail lines, next to the main lines. Dutch Railways (NS) operated the lines (The Hague – Rotterdam and The Hague – Zoetermeer), but suffered losses and saw declining ridership. Therefore, it was decided to transform the two lines into light rail lines. As The Hague has an extensive tram network and no metro, the city desired a low-floor tram towards Zoetermeer. Rotterdam desired an extension to its metro network and as such the line between Rotterdam and The Hague was converted to a high-floor metro. Resulting was a network of two regional lines that ran directly into the city centres. Ridership grew more than expected, and after ten years the system runs up to its capacity (Mott MacDonald, 2016).

For 5.6 kilometres, both lines use the same tracks, so a tram-train-like (actually a combination of tram-train and metro-train) scheme was developed. Although light rail is combined with metro, there is no interaction with real heavy rail. This makes the RandstadRail a Class C scheme. The entire line is electrified at 750V DC, and stations are modified to have high and low platforms. As the low-floor vehicles have wheels with smaller diameter than trains, several heavy rail points were replaced by ones that could be used by the tram-train vehicles (ten Heuvelhof et al., 2008).

A period of 3 months was taken to replace parts of the tracks, and downgrade the 1500V DC electrification to 750V DC, which proved too short. After a few weeks of operation, several derailments had taken place, one which had 17 injured (ten Heuvelhof et al., 2008). Some of the derailments were due to broken points, while others were due to errors in track design and driver inexperience with a new type of railway point (spring points) (OvV, 2008).

On the shared section, block signalling is installed. However, the block-based system was technically unable to reduce headways to the desired 60 seconds (ten Heuvelhof et al., 2008) and the design capacity was reduced to 30 tph. In practice, only 24 tph can be achieved. Moreover, the system does not allow two vehicles to call at the same station simultaneously (Mott MacDonald, 2016).

4.2.4 Class D

Class D tram-train are operated independently from other rail networks and generally follow the French approach as discussed for Class B. Analysed class D lines are in Nantes and Paris. In Lyon, a small regional network of Class D tram-trains is operated as well.

4.2.4.1 Île-de-France Tramway T4 (single line)

The main mode of public transport in city of Paris is the metro. However, due to its low operational speed, the metro does not cover the suburbs. RER trains (regional heavy rail) provide connections between the suburbs and the city centre. However, the line spacing of the RER in the suburbs is large. Therefore, disused railway lines are modernised to provide tangential connections between the RER lines.

Tramway T4 has a length of 7.9 km and serves 11 stops. Its termini are stations of RER B and E, providing an easy transfer towards the city centre. Tramway 4 makes use of an old railway alignment and is powered by overhead lines at 25 kV AC. The dual-mode tram-train vehicles can also operate under 750V DC. Works are underway to add a branch line to Montfermeil, which will be operated as a tram line, with ROW C alignment (T4, n.d.). This will create a situation in which only one type of vehicle is operated on both a tram and train network, without shared operations on either part.

The advantage of operating the line as tram-train instead of train is that traffic lights suffice for priority and fully protected level crossings are not required. However, tram speed on intersections is limited to 30 km/h and several minor accidents have occurred in the first year (Railwaygazette, 2007).

According to Railwaygazette (2007), the 8-km long line serves a population of 280,000 people and 90,000 workplaces. The new extension connects Clichy-sous-Bois and Montfermeil to the line, which together have over 55,000 inhabitants. Operator Transilien (2018) notes a daily ridership of 35,000 passengers.

4.2.5 Other reference projects

In this section, two Dutch tram-train projects are discussed that were planned and designed, but not implemented. In the RijnGouweLijn case, there has been a trial which has resulted in valuable lessons for future tram-train in the Netherlands. The area around Groningen resembles German cities such as Kassel and Chemnitz, which might indicate that tram-train would have worked there. For both the RijnGouweLijn and RegioTram Groningen, it holds that there was no existing tram network and public opposition against the tram networks lead to discontinuation of the projects (Van der Bijl et al., 2015).

4.2.5.1 RegioTram Groningen (Class A)

The city of Groningen is the largest and economically most important city in the northern part of the Netherlands. It has regional railways towards several towns in the region, and a main line towards the south. The city has no tram network, all public transport relies on buses. In 2009, a plan was made to construct two tram lines in the city, which could later be extended as tram-train towards the neighbouring villages. However, there was public opposition against the tram lines in the city centre. After some years, the project was abandoned by politics.

Especially the low frequency of regional trains (thus spare capacity on the tracks) and strong regional focus on the main city made the case of Groningen suitable for a tram-train scheme. Also, it is an example of how political instability can lead to abolishment of large infrastructural investments (Van der Bijl et al., 2015).

4.2.5.2 RijnGouwelijn (Class B)

In the Netherlands, a brown-field trial with tram-train vehicles has been performed, as part of the RijnGouwelijn project. The aim of the project was to connect the cities of Gouda and Alphen aan den Rijn to the city centre of Leiden, with future extensions towards the North Sea coast. Although the project was never completed due to political issues in Leiden and the province of Zuid-Holland, the trial itself was successful; providing valuable lessons to NS, ProRail (IM) and HTM (tramway operator).

The trial featured operation of a light rail vehicle (Bombardier Flexity Swift A32, similar to the Stockholm regional trams) on the regional line between Gouda and Alphen aan den Rijn, while the same line was still used by rush hour train services and a few freight trains.

4.3 Analysis of tram-train systems

Based on the reference systems which were studied in the previous paragraph, the typical system parameters of tram-train are determined. As tram-train is generally an extension of urban tram onto heavy rail, it is expected that the network parameters of the urban part of tram-train lines are not much different than those of regular tram networks. For the train part however, one of the advantages of tram-train is the good acceleration and deceleration characteristic of the vehicles allowing for extra stops, which is visible in the average stop spacing. This figure does not give the complete picture, because additional stops in villages will often have a small spacing, with a longer distance to the next town. However, a downside of this decreased stop spacing is the lower average speed. Between closely-spaced stops, tram-trains do not reach their maximum speed, and on longer sections the relatively low maximum speed of vehicles negatively influences the average speed.

4.3.1 Acquiring data of the existing systems

To determine the system parameters, each tram-train line has been analysed. The tram- and train sections were analysed separately and compared between the systems on five parameters, with some other parameters used as support (e.g. maximum speed for average speed). In most cases, the lengths of the sections were measured via Google Maps. Numbers of stops and trip times were determined via actual (September 2018) timetables. These figures were used to calculate the average stop spacing and average speed. The length and number of stops of a full line is calculated by summing the tram and train part, the trip time is retrieved from the timetable and the average speed and stop spacing are calculated as mentioned before. In some systems there is no tram or train section, or it is not perfectly clear to what category the line belongs.

- Nantes T2: full line has shared traffic with heavy rail, so treated as train section.
- RijnGouwelijn: the data is taken from the pilot project (PZH, 2006), which took place on a heavy railway line. Data on the proposed tram section was not available.
- Paris T4: the line in Paris is partly operated according to heavy rail characteristics (overhead power, signalling). However, the line has a ROW B alignment, which is unfit for train operation on intersections. Therefore, it is treated as a tramway.

The Karlsruhe system has evolved into a vast system with very long lines, even serving several large cities. Using data on the full lines results in unrealistic values for urban public transport systems (trip times of over 2 hours). These lines (S4, S5, S8) are analysed until the edge of the KVV (Karlsruhe operator) tariff area.

For each of the parameters, the average (mean and median), minimum and maximum values were determined. If the mean and median value were almost equal, the mean value was used for further research. As the dataset is small, large outliers greatly influence the mean value. In such cases, the median value is used. The full analysis is described in Appendix B.

4.3.2 Analysis of system parameters

To discover in what situations tram-train can be useful, it is necessary to know how tram-train is positioned in the public transport system. Therefore, the parameters of tram-train systems are compared to those of urban trams, and regional trams and trains. This gives an impression of what type of existing networks can be integrated into a tram-train line.

4.3.2.1 Comparing tram-train to its ‘parental’ rail modes

Table 4-1 compares the found data on tram-train to the literature data of regional trains and urban trams of Appendix A. The average tram section of tram-train matches the parameters of typical urban tram systems, although the lines are relatively short, and the average speed is somewhat higher. Class A and B tram-train lines need to be punctual at the entry point of the heavy railway, which means that they should also achieve a certain level of reliability on the urban stretch. This can be achieved by limiting the line length (Van Oort & Van Nes, 2009) and using large sections of ROW B alignment, which benefits both reliability and operational speed. When comparing the train sections of tram-train to regional trains, stop spacing and line length are on the low end of the range of regional trains, which also relates to the lower average speed. At low average speeds, long lines will be too long to provide attractive and competitive travel times. As mentioned, the low average speed results from the low maximum vehicle speed and close stop spacing.

In Table 4-2, a comparison is made between full tram-train lines and regional tram lines. The average stop spacing is on the high end of the range, but other parameters are like those of regional trams. From Table 4-1 and Table 4-2, it can be concluded that tram-train has features of the various modes, which combine into a system that is mostly comparable to regional trams.

Table 4-1: Comparing tram-train to regional train and urban tram.

Parameter	Regional train	Tram-train; train section	Urban tram	Tram-train; tram section
Mean line length	> 20 km	23.6 km	5 – 20 km	6.7 km
Mean nr. of stops	--	11	--	13
Mean stop spacing	2 – 5 km	2.4 km	200 – 600 m	450 m*
Mean speed	> 60 km/h	45 km/h	15 km/h	19 km/h
Mean trip time	--	32 minutes	--	20 minutes

Source: Appendices A and B.14. * Median value (outlier: Nantes T1: 5000m)

Table 4-2: Comparing tram-train to regional tram.

Parameter	Regional tram	Tram-train
Mean line length	10 – 40 km	32.6 km
Mean nr. of stops	--	25
Mean stop spacing	0.4 – 2 km	1.7 km
Mean speed	30 – 45 km/h	37 km/h
Mean trip time	--	55 minutes

Source: Appendices A and B.14.

4.3.3 Tram-train in the public transport network

It was found that tram-train is about developing existing infrastructure flexibly into a new system. Tram-train systems are found both in small cities and in metropolises but serve a different purpose. Three possibilities are distinguished when positioning a tram-train line in a public transport corridor: as main mode, secondary mode or feeder mode.

4.3.3.1 Main mode (All classes)

Tram-train as main mode provides the public transport between a city and a small or medium populated corridor. Regional train services between the city and terminus are completely replaced by the tram-train or operated as zonal express service (see section 2.2.2.3). Express tram-train services can be provided between larger towns. Ideally, a line can be transformed into class C or D, which reduces the requirements for tram-train vehicles. Nevertheless, track-sharing with long-distance and freight trains is possible, given the required frequency can be provided on the tracks.

4.3.3.2 Secondary mode (Class A & B, or parallel to heavy rail)

Tram-train as a secondary mode supports a train line and can be used in corridors with larger populations. Trains serve a single station in the larger towns, while tram-trains serve all settlements and possibly additional stops in large towns (local/express operation). This way, the larger cities have fast connections to railway hubs (by train), and direct connections to the main city centre (by tram-train). An advantage of a secondary mode tram-train is the possibility of speeding up the regional train, while the tram-train can be operated at lower frequencies. When the tram-train uses separate tracks, very high frequencies can be achieved.

4.3.3.3 Feeder mode (Class C & D)

A feeder tram-train line is a special type of secondary mode, and used as a tangential, lower-level service. It mainly provides connections to (radial) higher-level rail systems. Feeder systems are likely to be former railways transformed to class C or D lines, as most present-day train lines have radial structures around large stations. Feeder tram-train lines should offer high frequencies to provide seamless connections to the higher-level mode. The best example of a feeder tram-train line is the Parisian T4.

4.3.3.4 Frequency and transport capacity

The service level of public transport is to a large extent dependent on the offered frequency. While an hourly service is regarded as the minimum service level for basic travel needs, commuter rail services are typically offered twice or three times an hour. Four trains per hour are generally suitable for corridors with higher population densities (TRB, 2013). From the investigated systems, it follows that most class A/B tram-train lines have frequencies of once or twice per hour. The Sheffield-Rotherham line has a proposed frequency of 3 trams per hour.

From a service level point of view, a basic frequency for tram-train of 2 per hour should be offered. As secondary mode, a third (and fourth) service per hour can be run as express service. This way, larger towns have one or two express services and two local services to the city.

4.4 Advantages of tram-train

Before the introduction of tram-train around Karlsruhe, usage of public transport was limited. For instance, the Bretten – Karlsruhe section was used by around 2000 passengers each day. Only a year after the introduction of tram-train, ridership had grown by more than 400 per cent (Teule & Rienstra, 2000). By 2015, the same corridor serves over 18000 daily passengers (AVG, 2015). Other systems, such as the RandstadRail, have shown unexpectedly high increases in daily usage as well, indicating that well-functioning shared-running systems provide an attractive service to passengers. The attractive service is a result of several advantages that tram-train offers over other methods of (public) transport, which are described below.

Elimination of transfers

Tram-train is specifically designed to penetrate directly into attraction centres in cities, making transfers between heavy rail and urban public transport unnecessary (Van der Bijl & Kühn, 2004). Although the in-vehicle time increases due to the lower average speed, the transfer component is eliminated. This is especially beneficial when considering experienced travel time, due to the removal of the transfer penalty (Teule & Rienstra, 2000).

Relatively fast trips to the city centre.

At the heavy-rail sections, vehicles have full priority and can travel at line / maximum vehicle speed. This is generally higher than what would be possible on ROW B / C rail alignments. Compared to public transport buses, which mostly have a maximum speed of 80 km/h or lower (EC, 2018), tram-train vehicles capable of operating at 100 km/h can achieve faster trips.

Larger catchment area (smaller stop spacing)

Tram-train vehicles are relatively light. This allows fast acceleration and deceleration and enables them to serve more stops than a train would be able to (Teule & Rienstra, 2000). Furthermore, tram-train vehicles can leave the main tracks and run on tram alignment in larger towns. This provides quick access to regional public transport, such as in towns around Karlsruhe.

Transit-oriented development around high-quality stops

According to Calthorpe (1990), urban Transit Oriented Development (TOD) should be located along the trunk line network, at light rail stops or at transfer stations; high quality public transport locations. Tram-train at regular intervals can provide this high-quality public transport, and thereby support the development of TOD-areas.

Ability to bypass main railway stations

Tram-train lines that branch off heavy rail tracks onto street alignments can relieve congestion at main stations. Tram stops can handle vehicles at much shorter headways than stations, due to the absence of block protection systems. As found in section 2.1.2.1, train stations in dense cities can become bottlenecks in heavy rail capacity. By taking regional services off the main tracks onto street alignments, track capacity in stations can be reallocated for interregional and national services. However, this can increase the length of the (slow) urban section, which can lead to increased travel times.

Limited new infrastructure required

Tram-train uses existing tram- and train infrastructure. Therefore, it is not required to construct large amounts of new infrastructure which is especially beneficial in city centres. Building new infrastructure in cities causes disruptions to daily life and is very expensive. The only required infrastructure is a connection between the tram and train networks. However, the connection needs to be thoroughly designed, as it will be the changeover area for traction supply, operational principles and traffic control. Furthermore, by using existing infrastructure, land use plans can be adhered to. This saves cost and time that would be required for legal procedures on new infrastructure; such as noise, safety and environmental studies (Vreeswijk, 2018).

The connection in Kassel is a good example of a system in which limited new infrastructure was required to create a ‘new’ network. According to the Nordhessischer VerkehrsVerbund (NVV, 2006), less than 10 kilometres of track were constructed and thereby a RegioTram network of 122 kilometres was created. It should be noted that this included a tunnel under the main station, which still is a relatively expensive improvement. In Strasbourg, this was one of the reasons not to create a tram-train network (Bigot, 2014).

Cheaper infrastructural solution

Light rail infrastructure in cities can be constructed at a lower cost than new heavy rail (S-bahn / metro-like) infrastructure. Using on-sight operations saves cost on train protection systems and permits using regular traffic lights and tram warning lights at crossings with road traffic. Train lines require fully protected level crossings, which are much more expensive and have longer closing times for road traffic. This advantage is exploited in Nantes and Cardiff.

Enlargement of system scope without adding a new level

Donders (2018) notes that integrating existing tram and train systems in a city can increase the total coverage of an urban public transport system, without adding an additional layer (such as a metro network) to a public transport network.

Improved service on longer distance lines

As the tram-train serves local stops and towns near cities, train services that previously served such areas can be sped up. They do not need to call at these stations, which reduces the travel time to and from destinations further away (NVV, 2006). This improves the accessibility of a city for a larger region than only the part served by tram-train.

Ability to blend into pedestrian areas

Trams are exceptionally able to operate in pedestrian areas. The tracks clearly mark the presence of vehicles. Furthermore, at low speeds on straight sections, trams produce less noise than diesel buses (Janić, 2014), which creates less nuisance for pedestrians and residents.

Sustainability

In section 2.2.4 it was found that electrical, rail-bound modes have sustainability advantages over buses (both on particle emission and energy consumption per seat-kilometre). According to NVV (2006), the RegioTram vehicles used in Kassel can transport passengers twice as far as regular trains at the same energy consumption – accredited to the ability of regenerating braking energy. The light weight of tram vehicles also adds to the lower power usage of such vehicles.

Railbonus

As was noted in section 2.2.5, there exists a ‘railbonus’. As a result, the expected ridership of a tram-train line will be slightly higher than that of a bus line with the same operational parameters.

4.5 Disadvantages of tram-train

In the previous section, advantages of tram-train were discussed. However, combining two distinct systems has its challenges. This section lists several disadvantages of tram-train.

Specific rolling stock

Kühn (2018) notes that dual-system tram-train vehicles are more expensive than regular trams or trains. Tram-train vehicles are a niche and very specific type of vehicle. For each system, different vehicles are required and often only in small numbers. For example, a new (standard) Citadis for Lyon contract is awarded at €40m for 11 trams (€3.6m/unit) (Railway Techonology, 2018a), while the NS Flirt order was €280m for 58 trains (€4.8m/unit) (Railwaygazette, 2015). In contrast, the 8-vehicle order for the diesel/electric tram-train around Chemnitz cost €42.3m, a unit price of €5.3m (Metro Report, 2012).

To overcome this, Streeter (2018) notes that the Verband Deutscher Verkehrsunternehmen (association of German transport companies, VDV), together with an engineering firm and the operators in Karlsruhe, is developing a standardised tram-train vehicle. The vehicle should meet both the EBO and BOStrab regulations, as well as DIN EN 15227 level C3 crashworthiness requirements. Operators can still customise the standard vehicle to their specific desires, but do not need to go through full admittance procedures. Using a standardised vehicle can reduce both procurement costs as well as total cost of ownership, partly due to economies of scale, but also due to opportunities in having a combined reserve fleet. The foreseen standard vehicle is designed with a width of 265 cm, a maximum axle load of 10.7-11.5 tons and maximum speed of 120 km/h. As the design is made for German cities, the typical power supply is dual mode for 750V DC and 15kV 16 2/3Hz, but variants with diesel and batteries are envisaged as well. For other countries, sub-types of the basic design can be developed, to be operated under different voltages and train protection systems.

Political issues

In their analysis of many light rail projects, including tram-train, Van der Bijl et al. (2015) found several examples in which political disagreement resulted in dismissal of proposed projects. Tram-train is exceptionally prone to these disagreements due to the many stakeholders involved. Van der Bijl (2018) states that tram-train has the largest chance of success if there is one transit authority in charge for public transport around the urban region. In such cases, there will be one organisation that sets the requirements for public transport, instead of several municipalities.

The importance of political and institutional readiness is acknowledged by both Van der Bijl & Kühn (2004) and Naegeli et al. (2012) in their checklists on tram-train. Van der Bijl & Kühn mention that the best chance of success is when the infrastructural plans are supported by plans on urban development.

Institutional complexity

Developing a tram-train scheme requires local operators, regional/national operators and infrastructure managers to work together, both in getting the system technically interoperable and operationally functioning. It is important that all parties are willing to accept each other's capability and responsibility and sometimes not follow traditional principles (Kats, 2018). Organisational complexity can be a source of delay, for instance when certain parties are not fully cooperating (Kats, 2018) or when the project scope changes late in the process (ten Heuvelhof et al., 2008).

Local public transport operators are often owner of and maintain their own rail infrastructure. When tram-train uses heavy rail infrastructure, owned and maintained by an IM, the local operator needs to pay track and station usage fees (Van Oord, 2018).

Furthermore, a tram-train line can become a competitor to a TOC on suburban lines. Attention should be paid to the allocation of subsidies (if required) between the various operators. If the service quality improves due to the increased frequency, ridership can increase, which is beneficial to both companies.

Technical complexity

Tram and train are two technically separate systems. Heavy rail is designed to transport people over long distances at high speeds along separated infrastructure, while tram systems are designed to transport people over short distances with high accessibility in urban areas. Integration of the two technically different systems leads to certain challenges. Some issues can easily be solved, others can only be solved by complex or expensive measures and sometimes integration is not possible. These integration issues and solutions are discussed in detail in section 5.4 and appendix F.

One of the main technical issues is accessibility (Kühn, 2018). As tram-train often serves low-floor tram platforms and higher train platforms, it is difficult to provide full PRM accessibility. Sometimes, this can be arranged by specifically designing the vehicle, but increases the cost of the vehicles. The Karlsruhe system is not easily accessible to PRM (Kühn, 2018). Some solutions to this are provided in appendix F.2.3.

Operational complexity

In section 4.1.3 it was found that there is a difference between operational planning of trams and trains. If, in tram-train operation, a vehicle develops some delay on the urban section (due to traffic or long dwells), it might be too late to enter the heavy rail section in its designated path. Depending on the capacity occupation of the section, the vehicle should wait for a next path to be available. When capacity occupation of the train section is high, small entry delays of tram-trains can cause knock-on delays to other trains.

Furthermore, drivers must operate under two regimes; the train regime and the tram regime. Under the train regime, there is full priority to trains and no direct interaction with road users. The signalling system provides movement authority. When operating as a tram, the driver is in full control over speed and safely negotiating traffic and intersections. Signals can aid the driver (for instance during bad weather).

In section 2.2.2.3 it was found that long lines are more prone to travel time variability than short lines. Especially in combination with the required punctuality on train sections, delays from earlier along the line can cause vehicles to miss their path on the heavy rail network. Kühn (2018) notes that on some long lines with multiple sections of single track, delays on the various stretches can interact which worsens small delays.

Limited capacity

Urban tramways in ROW B and ROW C alignment can only handle a limited number of trams per hour, before the quality of pedestrian areas or crossroads is reduced due to the line of trams. If multiple tram-train and urban tram lines share a common corridor, the resulting frequency on the corridor can become too high. In Karlsruhe for instance, the success of the tram-train scheme stretched the number of vehicles on the tracks in the centre to the limit. Also, the relatively small tram-like vehicles cannot provide the transport capacity that regional train EMUs can at the same frequency. To provide similar transport capacities, the frequency should be increased.

4.6 Tram-train in the urban region

Although tram-train can combine advantages of both tram (accessibility and penetration within a city) and train (high speed) systems, there are limitations to its effectiveness. The effectiveness of a public transport system is also dependent on the city it is operated in. The area should match the strengths and weaknesses of a system. Van der Bijl & Kühn (2004) and Naegeli et al. (2012) have created qualitative checklists to determine the suitability of tram-train as a public transport mode in a city. The full checklists can be found in Appendix D. This section discusses the criteria on features of the city and region, and of the tram and train network. Compliance with the criteria described in this section is used as boundary condition when a tram-train suitability model is developed in chapter 5.

4.6.1 Population and structure of city and urban region

The way cities have developed over time plays an important role in the effectiveness of certain public transport modes. The capacity offered by a mode should match a city’s size: a metropolis such as London cannot only be served by buses, while a metro system is not efficient in a city of 50,000 inhabitants. Urban planning of cities and regions defines transport demands between cores.

4.6.1.1 City population

In literature (Van der Bijl & Kühn, 2004; Naegeli et al., 2012) it is mentioned that tram-train is generally not suitable for heavy metropolitan use. Naegeli et al. (2012) quantify that tram-train works well in cities with populations of 100 to 300 thousand residents. Analysis of the populations of the reference cities discussed in section 4.2, results in the histogram shown in Figure 4-7. Indeed, most cities have a population of 100 – 400 thousand inhabitants. The larger cities are The Hague and Sheffield, where tram-train is used as a secondary mode. A special case is the Parisian tram-train, which is used as a feeder service. The population around the corridor (250k) was considered, rather than the full city.

The concept of tram-train is not designed for inner-city transport, but to transport people from the region into the city. The actual city size is subordinate to that of the regional corridor, but in small cities (less than 100k inhabitants), bus networks are often more cost-effective than trams. Running small buses on higher frequencies provides a better service to passengers than running large trams on low frequencies. On the other side of the spectrum, metro systems are found in almost all cities with over a million inhabitants, where the fully closed system can achieve very high transport capacities. If tram-train is implemented in large cities, it should be supportive to the existing modes, and not add an additional network layer.

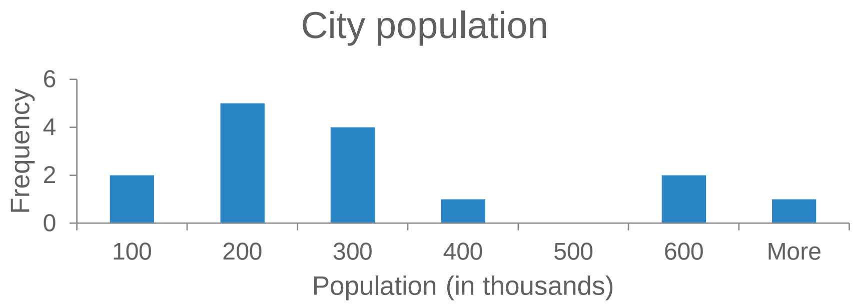


Figure 4-7: City population of analysed systems.

4.6.1.2 Population and size of the regional corridor

The choice for tram-train as access mode into a city instead of buses or regional rail largely depends on the corridor. The potential number of passengers, how dispersed and how far away from the city they live determine whether tram-train can fulfil expected transport demands.

Population and spread

Therefore, the served populations of the various systems were analysed. The main findings are presented here, while the elaborate analysis can be found in Appendix C. In Figure 4-8, for each system, the served population in terms of passengers per kilometre of corridor was plotted against the length of the corridor.

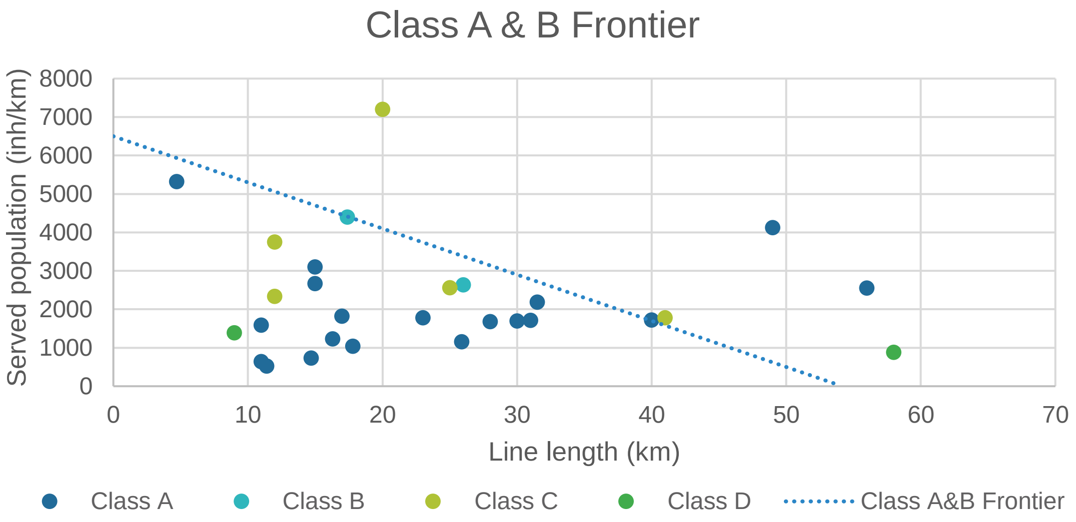


Figure 4-8: Served population and corridor length.

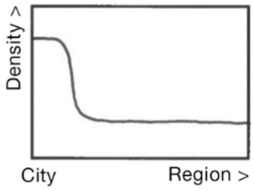
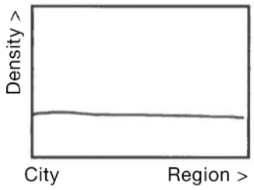
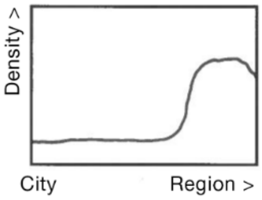
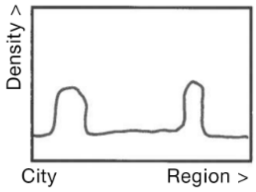
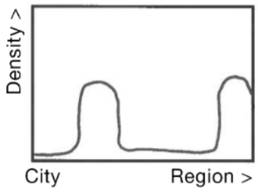
In the analysis of appendix C, it appears that there is no maximum size of a corridor. From Figure 4-8, a linear frontier, described by equation (2), was found below which a population size at certain line length can be served by class A and B systems. Two class A lines (Karlsruhe S7 and S8) are above the derived frontier. These two lines might be transformed back into train lines in the future (Kühn, 2018). Therefore, they can be accepted as outliers which do not fit within the frontier. A full derivation of the frontier is provided in appendix C.3.

$$\textit{Served population per line-km} < 6500 - 120 * \textit{length} \qquad (2)$$

In corridors exceeding the frontier, class C or D tram-train systems, or alternative modes are preferred.

Besides the absolute population, the spread of population along a proposed line influences the effectiveness of tram-train as public transport. The spread of the population along the corridor depends on whether all served villages are similar in size, or whether there are larger towns along the alignment. In Table 4-3, five types of spread and possible uses of tram-train are given.

Table 4-3: Population spread along corridor and tram-train possibilities.

	*A) High density near the city, lower near the end of the corridor.* Depending on the length, an extension of the urban tram network might provide better transport supply. If the high density extends for several kilometres, tram-train (with short-turning services) can be used as main mode.
	*B) Relatively even spread along the corridor.* Tram-train can be used as main mode. If the number of inhabitants per kilometre is above the frontier of equation (2), but below 4500, class C or D is advisable. Above 4500 inh/km, a higher capacity system will likely be required. Below 500 inh/km, a bus system will probably be more efficient.
	*C) High density near the end of a longer corridor, smaller settlements in between.* Depending on the density of the intermediate section, regional train + bus is advisable. For class A and B implementation, tram-train will likely be a secondary mode.
	*D) Some significantly larger cores, with sufficient population along the line, or less than 5km apart.* Depending on the size of the cores, tram-train can be a main mode or secondary mode. If tram-train can serve the larger cores on a tram alignment, secondary mode is most likely.
	*E) Few cores, more than 5 km apart, with little to no population in between.* Tram-train is not advised unless regional trains cannot achieve higher speeds. Transfer facilities should be improved instead.

In section 4.3.3.4 a basic indication of required frequencies for acceptable services was given. However, the required frequency also depends on the transport demand. Generally, tram-train vehicles have capacities of up to 250 passengers. This results in a line capacity of 500-1000 passengers per hour, depending on the offered frequency. If the demand exceeds this capacity, using double traction can increase the capacity per train.

Line length

Analysis of the length of the regional sections of the reference systems of section 4.2 gives a cumulative distribution as shown in Figure 4-9. Most regional sections are between 10 and 35 kilometres long. The absence of sections shorter than 10 kilometres can partly be explained by the focus on class A and B systems. For short distances, extension of the urban tram network is more cost-effective. In areas with high population density where tram-train serves as feeder, short lines can exist (e.g. Paris T4). However, these will likely be class D lines. For lines longer than 35 km, the average speed of tram-train becomes too low to provide an attractive service within an acceptable travel time (section 2.1.1.2). This is also reflected in the decision to shorten the long tram-train lines around Karlsruhe (Kühn, 2018).

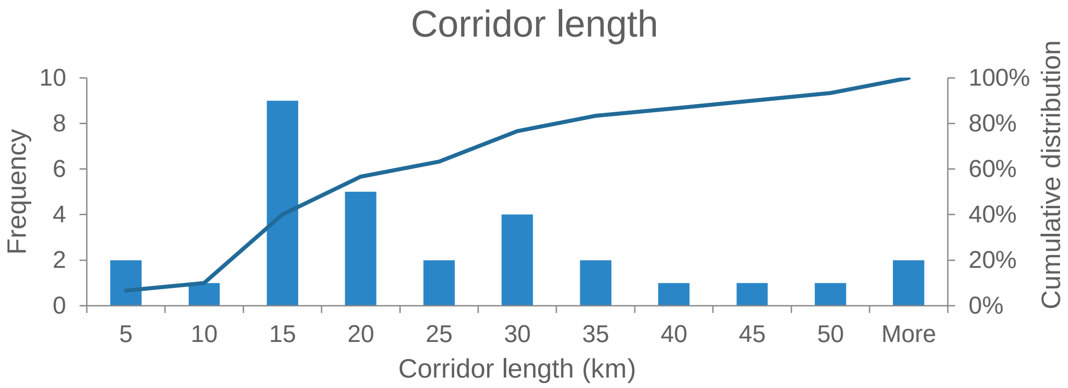


Figure 4-9: Frequency and cumulative distribution of the length of regional sections.

Population density in towns

Higher capacity public transport systems such as trams and metros are more efficient when many people live close to a corridor, for instance in high-rise or high-density terraced housing. In typical U.S. cities, population densities are much lower and spread over larger areas, which means that the number of people that can be served by a single stop is low. In such cases, a network of multiple lines with small vehicles can offer a better accessibility than a single line operated with large vehicles.

Therefore, the towns served by a tram-train line should have sufficient residential density around tram-train stops. Efficient access and egress modes can increase the coverage of a stop. Frequent tram-train services can be of sufficient quality to support TOD, which improves the feasibility of a line.

Presence of multiple regional corridors

When a tram-train network of several regional lines is created, it is possible that economies of scale can be obtained. This reduces the unit price of vehicles and allows more efficient allocation of resources. Van der Bijl & Kühn (2004) note that there are benefits when a large project can be achieved in steps.

4.6.2 Relation between the region and city

Focus on main city

Tram-train is designed to provide easy access from suburbs and towns towards a city centre. Both Van der Bijl & Kühn (2004) and Naegeli et al. (2012) observe that a radial tram-train works best in regions that are strongly focussed on its core city; both economically and socially.

Vreeswijk (2018) notes that a public transport line connecting two main cities via smaller towns has the advantage of peak demand into two directions, which ensures that there are very few empty trips. This is visible on the RandstadRail line between Rotterdam and The Hague.

Attraction centres

Public transport works well when there are locations where many people want to go regularly, such as business districts or city centres. These centres should draw enough demand to justify direct connections to other towns. Universities (especially in Europe) are important attraction centres as well, as students often use public transport. If the attraction centres are spread out over a city, a radial tram network (with good transfer nodes) might be better than a single tram-train line (Naegeli et al., 2012; Kühn, 2018). Ideally, a tram-train line towards a main attraction centre serves additional places of interest along its route.

The presence of attraction centres is also related to city size. Cities of up to 300,000 inhabitants are mostly too small to have two 'main' centres (Naegeli et al., 2012).

Location of main railway station

The location of the main railway station determines whether passengers walk from the station towards their destination or transfer to another mode. In many cities, main railway stations were built on the edge of cities (when there still was space) rather than near the centre. The distance between the station and city centre defines whether there is demand for a public transport corridor – elimination of the transfer is the main advantage of tram-train (Van der Bijl & Kühn, 2004). Naegeli et al. (2012) describe that from walking distances of 1 km and more (> 10 minutes), or when there are large elevation differences, people normally take a bus or tram to reach the centre.

The walking environment between a station and a corridor also influences the willingness of people to walk. The presence of sidewalks, safe intersections and retail improve the walking corridor, while large and busy intersections and poor personal security greatly reduce the willingness to walk (TRB, 2013).

4.6.3 Link to existing rail networks

Existing rail corridors into the city

Van der Bijl & Kühn (2004) note that for regions in which the rail network into the city centre is already well developed (S-Bahn / RER), tram-train might have little added value as addition to these corridors. Tram-train's most important characteristic is the elimination of transfers, which is already provided by the existing services.

If no tram network is present when a tram-train scheme is initiated, the city network can be designed to use the strengths of tram-train as much as possible. Also, it allows an optimal integration between the train and tram network as there are less constraints to consider. In Cardiff, the new tram network can slowly develop as a highly accessible, but less expensive extension to the train network (Briggs, 2018). However, when no tram network is present, the investment costs of the scheme will increase greatly. This eliminates the advantage of realising a relatively cheap network enlargement. Besides, the presence of a tram network allows people to travel further into the city easily.

If there is no heavy rail network present, tram-train is no option.

Possibility of connecting existing networks

The connection between the tram and train network is of prime importance to the functioning of tram-train, as it is the location where operational aspects and, if applicable, voltage change. Ideally, the changeover takes place on-the-move, which requires a section of sufficient length to construct a neutral section. A level section with good visibility on other tracks aids in ensuring an easy and safe transition. When the changeover area is located near a main station, this station can be used as a small buffer in the timetable, and for (un-)coupling of trainsets when required for capacity. In cases where a changeover area cannot be constructed at a suitable location or at a reasonable price, an alternative solution should be sought.

If the existing networks have different gauges, full track sharing will be complicated. A Zwickau-type of solution can be used, but a tram-train with full track-sharing will not be possible. A strength of tram-train is the possibility of gaining large network size increases by adding short connecting tracks. Dual-gauge will require infrastructural modifications over the entire shared section, which is very costly. There are situations in which a small section of dual gauge track sharing can still open up a new area, for instance at large river bridges.

4.6.3.1 Current tram corridor

Vehicle width

Old tram networks are often designed for narrow trams (width of 2.3 or 2.4m), as a narrow alignment has a better fit in old streets (Van der Bijl & Kühn, 2004). However, tram-train vehicles generally have a width of 2.65, which is the maximum width allowed by the BOStrab regulations. Using narrower vehicles on class A and B lines leads to additional technical issues at platforms, as was experienced in Kassel (Kühn, 2018). Besides, increasing vehicle width increases the capacity of a vehicle, as was described in section 2.2.1. Therefore, when tram-train is introduced, the existing tram network should be able to accommodate vehicles of the required width. This means that the entire corridor on which the tram-train will run should be checked for loading gauge issues and widened where required.

Remodelling a corridor to support 2.65m wide trams can be advantageous as it provides an incentive to redesign street alignments and upgrade old stops to new standards. However, on sections that are shared with existing narrow vehicles, the platform gap can become wider for these old vehicles.

Vehicle length

If the expected transport demand requires longer vehicles than currently used on the network, the existing platforms and track layout should be able to accommodate the longer vehicles or be easily modified. For instance, switches might need to be moved and platforms extended. Depending on the amount of required remodelling work, implementation of tram-train becomes increasingly expensive.

Level of service of urban tracks

The reliability of tram services depends on the right-of-way of the alignment. Trams in traffic are prone to congestion, which leads to travel time variability. Full tram-train lines are generally longer than urban lines, so travel time variability reduces the reliability of the service. Tram-train should be a form of high-quality transport, which includes proper punctuality. To be competitive with other transport modes, a high speed is required. Therefore, tram-train lines are preferably fully ROW B, except for pedestrian areas. On the ROW B sections, priority to tram-trains on intersections leads to improved operational speed and reduced travel time variability.

Pedestrian areas negatively influence the operational speed. In these areas, tram speed is often limited to 15 km/h for safety purposes. Long sections of pedestrian area reduce tram-train attractiveness as it impacts average speed a lot. Gauntlet track has a negative influence on the reliability of tram services as well because vehicles must wait for each other. Especially in busy areas or on longer sections, delays can be transferred onto following vehicles.

Moreover, for tram-trains using densely occupied heavy rail sections, the punctuality at the entry point is of great importance. A small delay in entry at the tracks can lead to knock-on delay to other trains or cause the tram-train to miss its designated path.

Tram corridor frequency

Although tram corridor capacity is not restricted by signalling systems, there are practical limits to the hourly number of trams. On ROW A alignments, capacity is virtually unrestricted, as there are few causes of disturbances. Considering dwell times and intersection delays, a minimum headway of around 3 minutes (20 tph) is expected to be acceptable for sufficiently reliable operations on ROW B sections.

4.6.3.2 Railway corridor

Tram-train vehicle speed

Tram-train utilises capacity on heavy railway lines, which should be available. Most tram-train vehicles have maximum speeds of 100 km/h, which is lower than most passenger trains. Although acceleration characteristics are superior to those of trains, the limited maximum speed is unfavourable on longer sections without stations. The proposed standard tram-train vehicle (Streeter, 2018) has a design speed of 120 km/h, which is beneficial for its capacity consumption. However, the effect of an increased vehicle speed diminishes when stop spacing is so short that vehicles are unable to travel at this speed.

Besides vehicle characteristics, the proposed frequency of a tram-train service determines the required track capacity. A higher frequency increases the attractiveness of the service, but requires more train paths, and hence consumes more track capacity.

Main station track- and stabling capacity

There are several examples in which not the corridor capacity, but the station throughput is limiting growth in the number of trains. In such cases, tram-train can reduce the number of local services required, by entering the city tracks before passing through the station. When the station is served via tram platforms, connectivity to other rail services can still be offered, although at a slightly lower transfer quality.

In case there is plenty of stabling capacity near a station, it is possible to use combined vehicles between suburbs and the main station, and split trains at the station. This way, additional transport capacity can be provided between the main station and suburbs, for passengers transferring onto longer distance rail transport. However, this requires a robust timetable, and increases operational costs due to the shunting movements.

Railway track layout

On shared sections, the available capacity also depends on the track layout. Quadruple tracks enable full separation of through and stopping services, or separation of trams and trains. Double tracks with sidings at stations also provide overtaking possibilities, but this requires trains to wait at stations. For low-frequency services, a single track with passing possibilities can be sufficient, but when tracks are shared with different types of train services, a full double-track configuration is a preferred minimum.

4.6.4 Access and egress

Cycling

In section 2.2.3, it was found that high-quality public transport stimulates cycling as access mode. If the offered service level of a tram-train service is of sufficient quality to promote cycling as access mode, the catchment area of tram-train stops can be improved. In this context, the quality of the offered public transport service also includes the facilities available for cycling.

It was noted that on the activity side of trips the share of bike-usage is lower than on the access side, possibly because of unavailability of bicycles on this trip end. Affordable public bike-sharing services can fill this gap and provide more efficient egress from tram-train stops. Although the stop spacing is sufficient to provide good walking accessibility, cycling can widen the range of tram-train within a city. However, efficient bike-sharing systems can also reduce the need for a tram-train system, as the bicycle will provide an alternative to the tram between a station and the final destination.

Access by regional public transport

A full integration of the tram-train timetable with regional public transport outside the city can increase ridership of tram-train, because it can be a faster modality towards the city and stretches the area from which people can reach the city centre with just one transfer (bus → tram-train) (Teule & Rienstra, 2000). In Kassel, this strategy is used to link communities and towns to the RegioTram network (NVV, 2006).

Similarly, small-scale group rapid transit (either along specified routes or demand responsive) might provide efficient access and egress modes in less densely populated areas or in industrial zones. Tram-train provides the mass transport, after which small vehicles spread the passengers towards their destinations (Metro Report, 2018).

Park & Ride

As noted in section 3.2.2, P&R facilities can reduce traffic pressure in cities. Combining park & ride with tram-train at stations outside the main city provides fast access to both railway stations (for long-distance travel) and attraction centres within the city. This can improve the viability of tram-train. Park & ride is an opportunity par excellence, as absence of such facilities does not negatively influence tram-train.

4.7 Conclusion

In this chapter, it was found that the concept of tram-train, has various implementation strategies. A classification scheme, based on whether tracks are shared with other trams or trains was introduced. The state-of-the-art was discussed for several systems, which show a great variety of implementations across Europe. For each of these, as well as for some proposed systems, the system parameters were analysed and compared to the ‘traditional’ modes urban tram, regional tram and regional train. Full tram-train lines can be compared best to regional trams, although there is a clear distinction in average speed and stop spacing between the urban and regional sections. Several criteria that provide the opportunity for a tram-train system were discussed: the population of the region, the relation between the city and the region, the (existing) rail systems and access & egress to the tram-train. Lastly, several advantages and disadvantages of the tram-train concept were discussed.

5 Evaluating applicability of tram-train

In this chapter, a methodology to evaluate the applicability of tram-train is developed, using a three-step model. In the model, it is determined whether tram-train is a suitable public transport alternative for a region. First, a quick scan checks whether tram-train is possible as a mode in a region. Secondly, a suitability scan using a multi-criteria analysis (MCA) performs an in-depth analysis of the criteria found in chapter 4. As a third step, technical feasibility of tram-train is determined.

The designed model is composed of three steps, following a top-down approach. The approach is outlined in Figure 5-1, which describes the objective of each model step and lists the required inputs.

A first step is the *quick scan*. Based on basic population parameters, presence of tram and train networks and heavy rail usage, it is analysed by means of decision schemes whether tram-train is possible at all, and how it would fit in the larger public transport network.

The second step is a more in-depth *suitability scan*, with a weighted-sum method (WSM) multi-criteria analysis. Fifteen criteria about the relation between city and region, existing tram & train networks and access & egress modes are investigated. The score for a criterion follows from a base score, and if applicable, bonus and penalty scores. This score is multiplied by a weight, and all scores are added to come up with a final score. The range in which the total score lies provides an indication of the suitability of tram-train. The suitability scan also includes a rough capacity estimation.

Lastly, a framework for the technical integration is developed. A library of interfaces between tram and train systems provides a reference checklist for technical integration. In this library, practical solutions to experienced problems are assessed qualitatively, which can be used as reference when a more detailed feasibility study into tram-train is performed.

After the first two steps, the output is an advice whether tram-train is an unrealistic alternative or a more or less suitable mode of transport for an investigated region. The third step gives an indication of relevant technical integration issues, with possible solutions. Figure 5-2 shows how the suitable solution space for a tram-train system is reduced by applying the three steps. If, during any of the steps, it turns out that the characteristics of the region lie outside the remaining solution space, tram-train will probably not be a possible solution.

As stated in the research question, the main objective of the designed model is to determine whether tram-train can provide certain improvements to a public transport network. Possible improvements were discussed in section 2.2. From the research objective (Figure 1-2), it follows that the desired improvements are to be treated as a constraint to the solution space. Therefore, the model requires the improvements as input. Whether tram-train can achieve the desired improvement is determined in a sensitivity analysis, as part of the suitability scan.

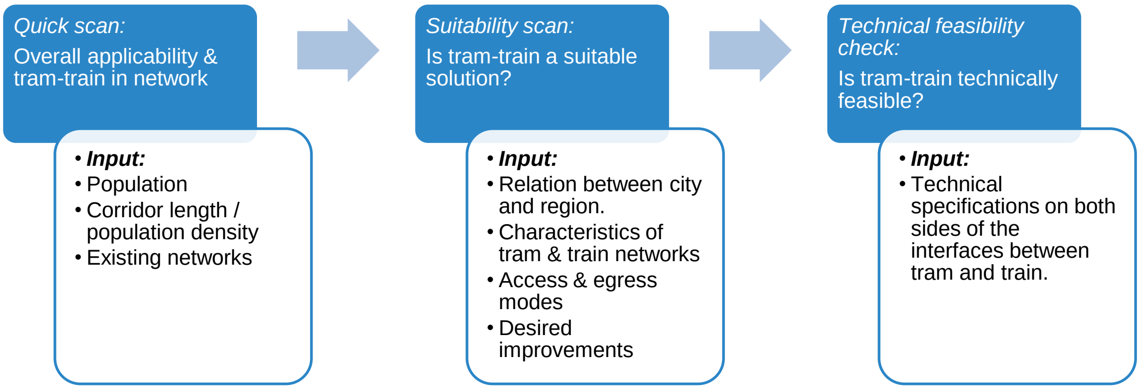


Figure 5-1: Outline of model steps.

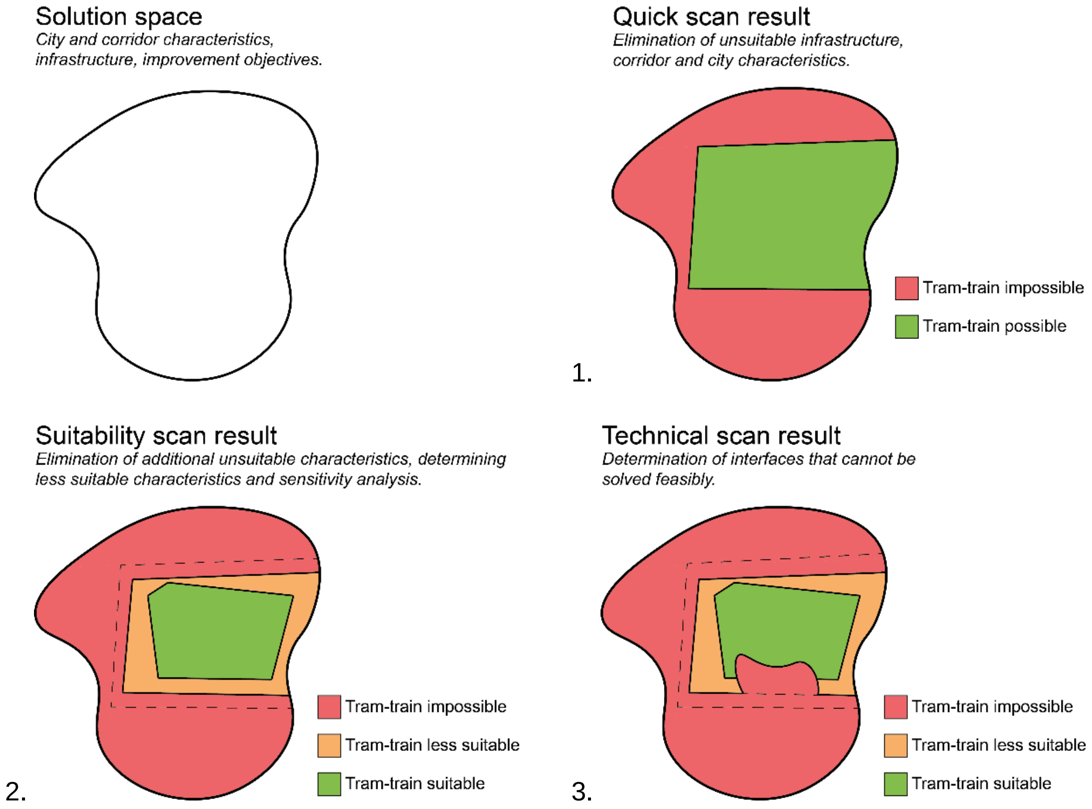


Figure 5-2: Reducing the solution space of tram-train in 3 model steps.

5.1 Quick scan

In the quick scan, it is assessed whether a tram-train system is a potential solution for an urban region. Secondly, the quick scan indicates what class of tram-train is possible, and whether tram-train can function as the main mode of transport in the urban area, or if it can be supportive to existing rail services, such as described in section 4.3.3. For instance, when some relatively large towns are connected to a city, it might be better to preserve existing heavy rail services (although not stopping at every station) to provide additional capacity and fast services to those who have the railway station as destination.

5.1.1 Quick scan methodology

The quick scan uses decision schemes to determine whether tram-train is possible for three main criteria, and what classes can be implemented. For each criterion, it is tested whether one of the classes and modes is possible, as shown in Figure 5-3. If at least one class and mode is possible, tram-train can be possible when regarding that criterion. The same process is repeated for all criteria. To determine the overall possibility of implementation of a certain class, it is analysed whether the class can be implemented for each criterion. If a class cannot be implemented for at least one of the criteria, that class is impossible. Determination of possible modes follows the same process as for the classes. The process is shown in Figure 5-4.

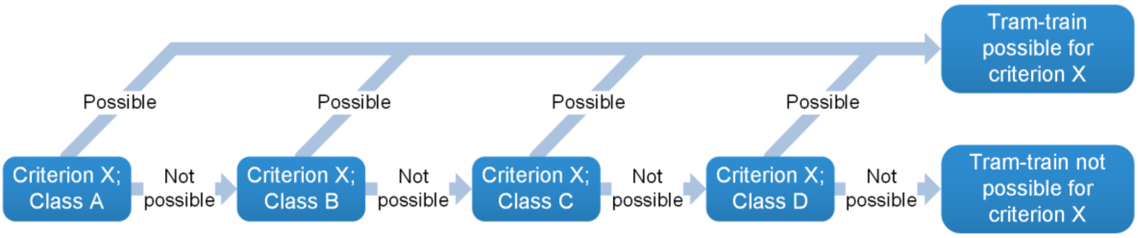


Figure 5-3: Decision scheme for possibility per criterion.

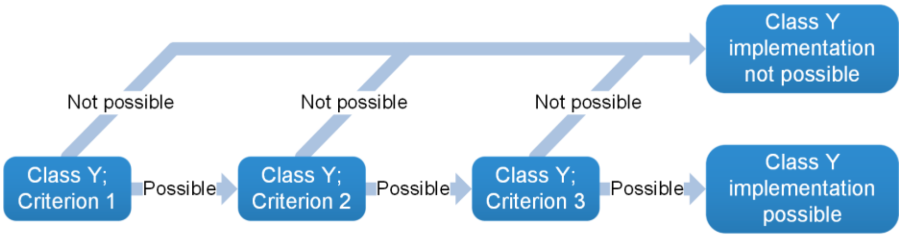


Figure 5-4: Decision scheme for possibility of implementation per class.

In the end, it might occur that tram-train can be implemented for each criterion independently, but not for the combination of all criteria. If, for one criterion only class C and D can be implemented, while for another criterion only class A can be used, there is no potential implementation. The process of determining overall implementation possibilities is provided in Table 5-1 and Table 5-2.

Table 5-1: Quick scan: determining possible classes.

Criterion	Class A	Class B	Class C	Class D	Overall applicability
Population and corridor	Yes / No	Yes / No	Yes / No	Yes / No	Yes, if at least one of the classes can be implemented.
Existing infrastructure	Yes / No	Yes / No	Yes / No	Yes / No	Yes, if at least one of the classes can be implemented.
Heavy rail usage	Yes / No	Yes / No	Yes / No	Yes / No	Yes, if at least one of the classes can be implemented.
Applicability of classes	Class A can be implemented, if yes on all criteria.	Class B can be implemented, if yes on all criteria.	Class C can be implemented, if yes on all criteria.	Class D can be implemented, if yes on all criteria.	Tram-train can be implemented, if possible for all separate criteria, and at least for one class and mode.

Table 5-2: Quick scan: determining possible modes.

Criterion	Main	Secondary	Feeder	Overall applicability
Population and corridor	Yes / No	Yes / No	Yes / No	Yes, if at least one of the modes is applicable.
Existing infrastructure	Yes / No	Yes / No	Yes / No	Yes, if at least one of the modes is applicable.
Heavy rail usage	Yes / No	Yes / No	Yes / No	Yes, if at least one of the modes is applicable.
Applicability of modes	Main mode is applicable, if yes on all criteria.	Secondary mode is applicable, if yes on all criteria.	Feeder mode is applicable, if yes on all criteria.	Tram-train can be implemented, if possible for all separate criteria, and at least for one class and mode.

5.1.2 Quick scan evaluation criteria

In the quick scan, three main groups of criteria are evaluated: population and corridor; existing infrastructure; and usage of heavy rail tracks.

5.1.2.1 Population and corridor

In section 4.6.1.1, it was discovered that most tram-train systems are found in cities with 100,000 to 400,000 inhabitants. Moreover, boundary values for the population and length of the corridor were defined.

In cities with more than 400,000 residents, it is expected that the transport demand exceeds the capacity which a class A or B tram-train system as a main mode can offer. For cities above a million inhabitants, tram-train can merely be used as a feeder service towards a metro or high-quality suburban rail system. A population of 100,000 inhabitants is assumed to be the lower boundary for tram-train to be a sensible solution. The model implementation of city population is noted in Table 5-3.

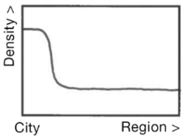
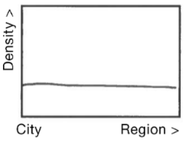
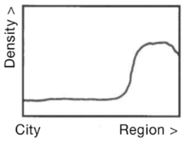
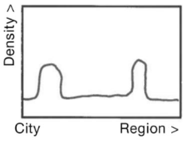
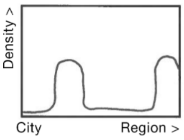
Table 5-3: Implication of city population.

City population	Applicable tram-train class and mode
< 100k	Too small for tram-train, a bus system will be more effective.
100 – 400k	All classes can be applied, both as main and secondary mode.
400k – 1m	Tram-train class A/B is possible as secondary mode, although unlikely there will be sufficient capacity. Class C/D can be applied.
>1m	Tram-train can be a feeder service to a higher quality and capacity system (metro, RER, S-Bahn).

In the analysis of the reference tram-train systems, no clear upper boundary for corridor population was found. However, the number of inhabitants per line-km indicates the possibilities. For class A and B systems, a frontier (equation (2)) was found, above which no class A and B systems currently exist. Excluding tram-train lines which only serve multiple cities (population spread type E), it was found that most corridors have more than 500 and less than 4500 inhabitants per line-km. For a feeder service, at least 25000 inhabitants per line-km are assumed to be required to provide sufficient transport demand. This assumption is based on, but lower than the single example; the Parisian T4, which has 35000 inhabitants per line-km.

In Table 4-3, five possible population spread types along the regional corridor, and their implications on tram-train were identified. The results are summarised for usage in the model in Table 5-4. Feeder systems are likely to be used within a city, therefore the spread of the population in a corridor is not relevant. For lines serving only larger cities (population spread E), tram-train is in principle not advised. For corridors with spread A and C, it is checked whether the population along the rural line (excluding the cities) is above 500 inh/km. Below this value, a bus system will likely be more cost-effective.

Table 5-4: Implication of population spread.

Spread type	Class possibilities	Mode possibilities	Notes
A 	A / B / C / D	Main	Population along low-density part preferably > 500 inh/km.
B 	A / B / C / D	Main	
C 	A / B / C / D	Main / Secondary	If class A/B and a large population, then secondary is advised. Population along low-density part preferably > 500 inh/km.
D 	A / B / C / D	Main / Secondary	If the larger cores can be served on tram alignment, secondary mode is most likely.
E 	A / B / C / D	Main / Secondary	Tram-train only realistic if tram-train vehicle speed is equal to the line speed. Otherwise, improved regional services are advised.

In section 4.6.1.2, the corridor length of existing systems was identified. It was found that 80 per cent of the lines have a length between 10 and 35 kilometres. For shorter lines, it is likely that the complexity of class A / B lines is higher than the benefits it can provide, and an extension of the tram network is more beneficial. On the other hand, for lines above 35 kilometres, a sufficiently high speed should be offered. Table 5-5 shows the implementation in the model.

Table 5-5: Implication of proposed corridor length.

Corridor length	Tram-train implementation
0-10 km	Only as feeder, otherwise it is advised to extend the urban tram network.
11-35 km	Tram-train can be applied.
36-50 km	Suboptimal, a high speed should be realised to offer competitive travel times.
> 50 km	No-go, too long to offer attractive services.

If a corridor is already served by high-quality rail services into the city, tram-train will probably not be a sensible addition to a public transport network, unless envisioned as feeder service.

5.1.2.2 Existing infrastructure

Tram-train is about extending services on heavy rail onto an urban network. Therefore, if there is no heavy rail network, tram-train is not a possible mode. When there is a heavy rail network, the possibilities for tram-train depend on the presence of a tram network, whether there is the possibility and intention to use said network for tram-train, and the possibility of constructing new tramways through the city. Table 5-6 shows the relevant combinations and the outcome for the tram-train analysis. In scenario I.4, class B/D is possible when existing tram services are replaced by the tram-train, although this is assumed to be unlikely. Apart from scenario I.2, in which tram-train can only be used as a feeder line, there is no implication on the possible modes.

Table 5-6: Possibility of tram-train classes based on infrastructure.

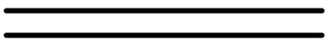
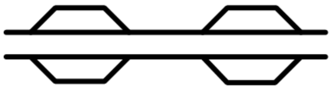
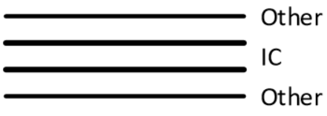
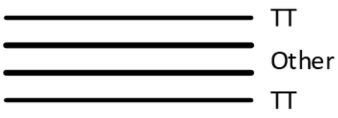
Scenario	HR infra present	Tram infra present and usable	Constructing a new tramway possible	Result
I.1	No	Not relevant	Not relevant	Tram-train not possible.
I.2	Yes	No	No	Tram-train only possible as Class D, feeder line.
I.3	Yes	No	Yes	Class B/D possible.
I.4	Yes	Yes	No	Class A/C possible. Class B/D unlikely.
I.5	Yes	Yes	Yes	All classes possible.

Note: The present tram infrastructure is only usable if the gauge is equal to the heavy rail gauge.

5.1.2.3 Usage of heavy rail tracks

In class A and B systems, the tracks are shared with other trains. In some cases, there are a few freight trains per day (Hoekse Lijn), while some lines in Karlsruhe share their tracks with multiple other trains per hour. In sections 2.2.1.2 and 2.2.2.3, it was found the capacity of railways depends on many factors. Therefore, a detailed capacity analysis on the specific corridor is always required, and the designed quick scan can only provide a very rough indication of the possibilities on the heavy rail tracks. Commonly, six types of track layout are used. These are shown in Table 5-7.

Table 5-7: Commonly used track layout types and implication on tram-train.

	*A) Single track.* Tram-train is probably not possible for longer distances, as only very low frequency shuttle services can be run.
	*B) Single track with passing possibilities.* Tram-train is possible, but reliability and frequency can be an issue. The capacity depends on the number of and distance between passing sections. Combining with intercity or freight services can be difficult and result in long dwell times for tram-trains.
	*C) Double track.* The capacity depends on the heterogeneity of the services, the distance between stops and the maximum speed the trains can achieve. On longer sections, a very heterogeneous traffic mix with large speed differences will result in a limited capacity.
	*D) Double track with overtaking possibilities.* The capacity is higher than on a C-layout, as fast trains can overtake slower trains. This reduces the minimum headway between various services. The more homogeneous the traffic mix, the higher the capacity, because less overtaking movements are required.
	*E) Quadruple track.* Intercity services have two dedicated tracks, while tram-train, regional and freight trains share the other. If regional and freight trains cannot overtake the slower tram-trains, the capacity can be more constrained than in layout D. However, in practice overtaking will likely be possible at some locations. In such cases, the layout is a combination of D and E and a high capacity can be achieved.
	*F) Quadruple track with two dedicated tram-train tracks.* A tram-like schedule with up to 20 tph is possible due to the fully homogeneous traffic on these tracks. If there is no interface to regular traffic (e.g. at stations), class C/D implementation is advised.

Possibility of class C/D and tram-train replacing regional services

To find the possible modes tram-train can fulfil, it is necessary to know whether tram-train can replace existing regional services. This is only a likely option if the current regional services are not much longer than the proposed tram-train services. Cutting a regional line at a proposed tram-train terminus results in an obligatory transfer for passengers, which is undesirable. In the long run, it might be beneficial from a technical integration point-of-view, to construct a slightly longer tram-train line than initially planned if this results in the possibility of creating a class C or D line. Table 5-8 shows the implementation of this criterion in the model. Whether tram-train can replace the current regional services is used as input variable. If there are no other heavy rail services on the proposed line, class C / D implementation is possible, as indicated by scenarios F.3 – F.5. Scenarios F.1 and F.2 indicate situations in which heavy rail services cannot be replaced.

Table 5-8: Implication of other train services on tram-train class C/D.

Scenario	Track layout	Regional frequency	IC / freight frequency	T-T can replace regional	Result
F.1	B – E	Not relevant	≥ 1 tpd	Not relevant	Class C/D not possible.
F.2	B - D	≥ 1 tpd	None	No	Class C/D not possible.
F.3	B – D	≥ 1 tpd	None	Yes	Class C/D possible.
F.4	B – D	None	None	Not applicable	Class C/D possible.
F.5	F	Not relevant	Not relevant	Not relevant	Class C/D possible.
F.6	A	None	None	Not relevant	If shorter than 15 km, class C/D possible.

Notes: If there is only 1 type of train service, track layout E can be regarded as layout F.
tpd = train(s) per day

Possibility of class A/B

The possibility of tram-train sharing the heavy rail tracks with other train serves depends on the available capacity on the heavy rail network. Preferably, an indication of the available slots for tram-train is given as input. Otherwise, Table 5-9 gives a rough estimation of the options for class A/B tram-train for several combinations of track layout, shared section length, and frequencies of other services. The table was developed with the aid of a timetabling expert. The assumptions are listed below the table.

For track layout B, it is assumed that intercity or freight trains should not be halted at passing loops. Therefore, a very high punctuality or much slack is required to ensure that tram-trains are at the right location when a crossing through-going train passes. For long sections, this is likely not a realistic demand and hence tram-train might not be an option.

Table 5-9: Possibility of applying class A/B tram-train for combinations of track layout, shared section length, and frequencies of other services.

Track layout	0-5 km	5-15 km	15-25 km	25+km
A	Not impossible, but limited frequency	Not impossible, but only low frequency*	No-go	No-go
B	Probably possible	IC ≥ 2 unlikely Limited frequency	IC / FR ≥ 1 unlikely Limited frequency	IC / FR ≥ 1 probably impossible Limited frequency
C	Probably possible	Probably possible Limited frequency when multiple other services.	IC > 4 unlikely RR + FR > 6 unlikely Limited frequency when multiple other services.	IC > 2 unlikely RR + FR > 4 unlikely Limited frequency when multiple other services.

Track layout	0-5 km	5-15 km	15-25 km	25+km
D	Probably possible	Probably possible	Probably possible	Probably possible
E	Probably possible	Probably possible	RR + FR > 6 unlikely**	RR + FR > 4 unlikely**
F	Probably class C/D	Probably class C/D	Probably class C/D	Probably class C/D

Notes: Frequencies in trains per hour. RR = Regional train; FR = Freight train; IC = Intercity train.
Assumed that tram-train is significantly slower than an intercity, and somewhat slower than a freight train or regional train. Assumed that there is a relatively regularly distributed (hourly) pattern. Assumed that tram-train services wait for IC/Freight trains at passing loops, and that those do not need to come to a complete stop.
* This is based on the Kamperlijntje in the Netherlands. Two services per hour are offered on a line of 13 km.
** If overtaking is possible at some places, a combination of layout D and E exists, and tram-train is probably possible.

Mode possibilities

Considering the heavy rail usage, tram-train can always serve as main mode, although unlikely in large corridors alongside regional trains. The possibilities for secondary or feeder services depend on the class and the possibility of tram-train replacing regional services. For feeder services a track layout C or better is required, as these are typically operated on high frequencies (TRB, 2013). In Table 5-10, the possible modes for several scenarios of tram-train class and other services are listed.

Table 5-10: Mode possibilities based on heavy rail usage.

Scenario	Heavy rail usage and tram-train class	Track layout	Possible modes
M.1	Class A/B, and tram-train replaces regional trains.	Any	Main
M.2	Class A/B, with no regional trains.	Any	Main
M.3	Class A/B, but tram-train does not replace regional trains.	Any	Main, Secondary*
M.4	Class A/B, with less than 3 freight trains per day	C – F	Feeder
M.5	Class C/D possible.	Any	Main
M.6	Class C/D possible.	C – F	Feeder

* The decision for main or secondary mode depends on the number of stations which should be served by the regional train. In large corridors, secondary is more likely.

5.2 Suitability scan

In the suitability scan, a multi-criteria analysis provides a better indication whether tram-train is a suitable option to provide certain improvements to the urban public transport, based on compliance to criteria described in section 4.6. The suitability scan also includes a very rough capacity estimation, based on inputs in the quick scan and some criteria of the suitability scan.

5.2.1 Suitability scan methodology

In the suitability scan, the weighted-sum method (WSM) will be used to perform the multi-criteria analysis. This method is the most widely used method for multi-criteria analyses (Triantaphyllou, 2000; Kahraman, Birgün & Yenen, 2008; Dodgson et al., 2009). The method, as described by Triantaphyllou (2000), is used to compare various alternatives directly. A score per criterion s_j is multiplied by a weight w_j. In the end, all intermediate results S_j are added up, which results in the end score of an investigated alternative; equation (3). The alternative with the highest score is the preferred option.

$$End\ score = \sum Sj = \sum_{j=1}^{n} s_j * w_j \qquad (3)$$

With n = number of criteria, j = nth *criterion*

In this research, the method is used to compute an end score which is used to define the suitability of a proposed line. The suitability of a corridor depends on what range the end score lies in. The corresponding ranges are based on reference systems and will be defined in section 5.2.4. This way, an analysed line is compared to the scores of the reference systems implicitly, analogous to a typical MCA. Four predefined outcome ranges are identified:

i. Tram-train is probably not a realistic alternative for the investigated corridor.
ii. Tram-train can probably be used in the investigated corridor but is not a very suitable alternative.
iii. Tram-train can be used in the investigated corridor and is a suitable alternative.
iv. Tram-train can be used in the investigated corridor and is a very suitable alternative.

Set-up of the analysis

In section 4.6, several criteria regarding the applicability of tram-train are discussed. Many of the sub-sections contain multiple criteria, which are all supportive to the sub-section criterion. Dodgson et al. (2009) advise that criteria can be grouped into a distinguishable series of sets. They note that grouping criteria eases the determination of weights and aid in checking whether the set of criteria is sufficient to take a decision. Moreover, they advise that typically between 6 and 20 criteria are used in an MCA. Therefore, for the suitability scan, it was decided to maintain the hierarchy, which results in 15 main criteria with several sub-criteria. The sub-criteria are used to develop a substantiated score for the main criterion.

The sub-criteria were sorted on importance to their main criterion. For each criterion, the one or two most important sub-criteria are regarded as baseline sub-criteria. Other sub-criteria are beneficial or unfavourable, but not important enough to fully define the score of the main criterion. These lower-level sub-criteria are regarded as bonus or penalty factors.

Determination of input scores

Input for the proposed model follows from compliance to the sub-criteria. Several sub-criteria are posed as yes/no-questions, which results in a binary input into the proposed model. Other criteria require categorical or ordinal input data. For categorical data, each category is awarded a certain score, depending on how well it adds to the suitability of tram-train on a given criterion. Ordinal data is the most difficult to convert to a numerical value, as it is impossible to define exact borders between options. In a few cases, an absolute value is requested (e.g. vehicle width, or amount of newly constructed tracks). These ratio values are converted into categories, after which the result is treated as categorical data.

Normalisation of the scores

An MCA consists of two steps: scoring and weighing. To preserve the indicative value of the weights w_j, all scores should be normalised (Dodgson et al., 2009). When applying weights to normalised scores, the value of the weight truly represents the importance of a criterion. The inputs for the suitability scan do not follow from similar data types. Some sub-criteria have nominal data, others have ordinal data and a few sub-criteria have data which results from categorisation of ratio data. Therefore, normalisation of the scores is required, so weights do not need to compensate for a low base score, e.g. due to binary data.

All scores are normalised to an interval in [0, 5]. The least suitable condition receives 0 points, the most suitable condition is awarded 5 points.

Application of bonus/penalty factors

Not all main criteria have the same number of bonus or penalty sub-criteria. Therefore, a maximum bonus and penalty score is set. This way, criteria with multiple bonus factors are not advantaged over those with less bonus factors. If two or more penalty or bonus factors are present, their individual score [-2, 0] or [0, 2] is multiplied by a factor (0, 1), with the sum of all factors being 1. Generally, factors are divided evenly (1/2 for 2 sub-criteria, 1/3 for 3, etc.), but if one of the bonus/penalty-factors is more influential than another, this is reflected in the factors and clearly substantiated. After applying the bonus and penalty factors, the score of a criterion s_j is in [0, 7].

Main criteria without a bonus or penalty sub-criterion are not compensated for this, as this can only be done relatively arbitrarily and thereby influence the outcome in an uncontrolled manner.

Boundary conditions

In a multi-criteria analysis, many criteria are treated. Consequently, the influence of single criteria on the end score is limited, as a low score on one criterion can be compensated by a high score on another (Dodgson et al., 2009). For tram-train, certain criteria have threshold values which should be adhered to and may not be compensated. If an analysed corridor does not comply with one or more threshold values, tram-train is probably not a realistic alternative and it is advised to search for alternative modes. Therefore, the threshold sub-criteria are treated as boundary conditions in the analysis.

Weighing of criteria

According to Dodgson et al. (2009), it is often more difficult to accurately determine the weight for each criterion than to score an alternative. Weights often follow from subjective reasoning, while scores can be determined objectively. Therefore, it is decided to use expert judgement to determine the weights to the criteria. Five experts, from academia as well as practice, were asked to reflect on the completeness of the set of criteria and to give relative weights to each of the criteria. Their judgements, and the resulting weights for the MCA are outlined in Appendix E.1.

5.2.2 Suitability scan criteria 1-15: MCA criteria

In section 4.6, several criteria for the applicability of tram-train were discussed. In the quick scan, a number of these criteria were used to determine whether tram-train can be implemented at all. In the suitability scan, the remaining criteria are treated, divided over 15 main criteria in four categories. In the expert judgement sessions, it was enquired whether these criteria yielded a complete overview for tram-train. The experts agreed that the list provides a sufficient overview, although some additional criteria (e.g. institutional context, financial aspect) were mentioned. However, these are out of scope for this research. In the following sub-sections, a brief description and the model implementation of each criterion is provided.

I. Population and structure
    1. Population density of towns along the corridor
    2. Possibility of developing multiple corridors
II. Relation between region and city
    3. Focus of region on city
    4. Presence of attraction centres in the city
    5. Distance between main station and attraction centre
III. Public transport network
    6. Possibility of connecting tram and heavy rail network
    7. Vehicle width
    8. Vehicle length

9. Service quality of urban alignment
10. Frequency on tram network
11. Service at main station and stabling capacity
12. Design speed of tram-train vehicles

IV. Access and Egress
    13. Bicycles
    14. Regional public transport
    15. Park & Ride

5.2.2.1 I. Population and structure

Criterion 1: Population density of towns along the corridor.

The possible transport demand for a tram-train system depends on the number of people that live around stops. The population per line-km as determined in the quick scan gives a rough estimate, and the population density adds value to that information. Low residential density implies that there are few people living in the catchment area of a station. As tram-train is a medium-capacity form of transport, medium -and high-density housing around stations will likely generate sufficient transport demand and are scored 4 and 5 points, respectively.

If the boundary condition is fulfilled, tram-train is not a realistic alternative. A bus system can provide better coverage through low-density towns. Alternatively, some form of DRT or GRT can improve accessibility of single stations in low-density residential areas, which is assessed in criterion 14.

Table 5-11: Implementation of criterion 1 in the suitability scan.

Crit.	Type	Description and input options
1.1	Baseline	What is the typical residential density around stations in the region?
	Input options	A) Very low (0); B) Low (2); C) Medium (4); D) High (5)
1.2	Bonus	TOD is already or can be developed around stations.
	Input options	A) Not (0); B) TOD can be developed (1); C) Some form of TOD already present (2)
1.3	Bound. cond.	Density around regional stations is very low, probably too little demand.
	Conditional	True if 1.1 is very low.

Criterion 2: Possibility of developing multiple corridors.

If there are possibilities to extend the tram-train network over multiple corridors, this can lead to economies of scale and attract more passengers to the system.

Table 5-12: Implementation of criterion 2 in the suitability scan.

Crit.	Type	Description and input options
2.4	Baseline	Are multiple corridors envisioned?
	Input options	No (0); Yes (5)

5.2.2.2 II. Relation between region and city

Criterion 3: Focus of region on city

If a region has a strong economic and social focus on its main city, this results in transport demand towards the city. Ideally, there is a strong or very strong focus on the main city (Van der Bijl & Kühn, 2004). Therefore, these categories are scored 4 and 5 points, respectively. In special cases such as the Rotterdam – The Hague RandstadRail, there is peak demand in both directions, which improves occupancy of vehicles in both directions. Hence, this is regarded as a bonus factor. On the other hand, if there are several large cores in a region which lead to very dispersed flows of passengers, a bus network might provide more flexible and efficient public transport than rail-bound modes.

Table 5-13: Implementation of criterion 3 in the suitability scan.

Crit.	Type	Description and input options
3.5	Baseline	How much is the region focused on the analysed city?
	Input options	A) Little (0); B) Mildly (2); C) Strongly (4); D) Very strongly (5)
3.6	Bonus	There is peak demand in two directions.
	Input options	No (0); Yes (2)
3.7	Bound. cond.	Several cores with very dispersed transport flows.
	Input options	No; Yes

Criterion 4: Presence of attraction centres in the city

One of the main ideas behind the tram-train concept is the ability to directly connect regional towns to attraction centres in a city. Therefore, at least one attraction centre with sufficient demand should be present. Bonus points are awarded when additional small attraction centres (high schools, hospitals, small shopping centres) or large educational institutions (universities / colleges) can be served by the tram-train, with extra weight on the latter. If a city only has several small attraction centres which cannot be served by a single line, there might not be enough demand to justify a tram-train line. A (radial) tram network with good transfer facilities might provide a better service.

Table 5-14: Implementation of criterion 4 in the suitability scan.

Crit.	Type	Description and input options	Factor
4.8	Baseline	At least one attraction centre with sufficient transport demand present.	
	Input options	No (0); Yes (5)	
4.9	Bonus	Additional small attraction centres served along proposed (city-)corridor.	0.4
	Input options	A) None (0); B) Some (1); C) Several (2)	
4.10	Bonus	Large educational institutions (university, college) directly served by tram-train line.	0.6
	Input options	No (0); Yes (2)	
4.11	Bound. cond.	Attraction centres are spread out over the city, a single line will not have enough direct transport value.	
	Input options	No; Yes	

Criterion 5: Distance between main station and attraction centre.

The walking distance between a train station and the main attraction centres justifies the need for tram-train. If the main attraction centre is located adjacent (≤3 minutes walking time) to a train station, there are already regional connections available and tram-train will not have much added value. Walking distances of more than 9 minutes were found to be very beneficial to public transport usage. As tram-train also eliminates a transfer, walking times of more than 6 minutes are scored 3 points and higher.

The base score for this criterion depends on the walking time (80%) and height difference (20%) between the station and attraction centre. Bonus points are awarded if the walking corridor is of poor quality, while a pleasant walk motivates people to walk a little further. Hence, this leads to a penalty. Another bonus is awarded if the walking corridor has poor personal security. For instance, a nice park can be an unpleasant place at night. In the expert judgement sessions, it was noted that the bonus/penalty factors are relatively unimportant compared to the baseline. Therefore, the bonus/penalty score for this criterion is limited to [-1, 1].

Table 5-15: Implementation of criterion 5 in the suitability scan.

Crit.	Type	Description and input options	Factor
5.12	Baseline	Walking time between main attraction centre and station.	0.8
	Input options	≤3’ (0); 3’<t≤6’ (1); 6’<t≤9’ (3); 9’<t≤14’ (4); ≥15’ (5)	
5.13	Baseline	Elevation difference between main attraction centre and station.	0.2
	Input options	A) None (0); B) Slight difference (2.5); C) Large difference (5)	
5.14a	Penalty	Attractiveness of walking corridor.	
	Input options	A) Very attractive (-1); B) Slightly attractive (-0.5)	
5.14b	Bonus	Unattractiveness of walking corridor.	0.5
	Input options	C) Neutral (0); D) Slightly unattractive (0.5); E) Very unattractive (1)	
5.15	Bonus	Walking corridor has poor personal security.	0.5
	Input options	No (0); Yes (1)	
5.16	Bound. cond.	Main attraction centre is adjacent to main train station.	
	Conditional	True if walking time is <4 minutes.	

Note: Sub-criteria 5.14a & 5.14b form a single sub-criterion but are split up as the factor for penalty and bonus are not equal.

5.2.2.3 III. Public transport network

Criterion 6: Possibility of connecting tram and heavy rail network.

An important aspect of tram-train is the possibility of connecting the two networks to each other. Therefore, a suitable location should be available, preferably with plenty of space for a tram-train to wait without holding other vehicles, and with good lines-of-sight onto the tram tracks. Preferably, multiple alternatives for a connection are available. In practice, a neutral availability of locations is sufficient and therefore awarded slightly above average (3 points). A small bonus is awarded for connections near train stations, as this improves the transport potential. If a single connection track opens the possibility of creating multiple regional lines, the effectiveness of such an investment can be high (e.g. in Kassel). On the other hand, if several connections are required for a single line, a larger investment might be required for less benefit. If there are no suitable locations or the connection becomes more expensive than foreseen (large civil works required), tram-train is probably not the optimal solution. Similarly, if there are track gauge differences between the two systems, tram-train cannot be implemented easily. There might be possibilities if dual gauge is only required for short sections (such as a bridge) but this is excluded in the scan.

Table 5-16: Implementation of criterion 6 in the suitability scan.

Crit.	Type	Description and input options	Factor
6.17	Baseline	Availability of locations to connect the tram and train network.	
	Input options	A) Poor (0); B) Neutral (3); C) Good (5)	
6.18	Bonus	The connection can be made near a train station.	0.3
	Input options	No (0); Yes (2)	
6.19a	Penalty	How effective can the connections be used?	0.5
	Input options	A) More than one connection required for a single line (-2); B) One connection required for a line (0);	
6.19b	Bonus	How effective can the connections be used?	0.7
	Input options	C) One connection enables creation of multiple lines (2)	

Crit.	Type	Description and input options	Factor
6.20	Penalty	There are available locations, but there is only limited space or difficult terrain (line-of-sight, inclination, curves, relatively long track required).	0.5
	Input options	No (0); Yes (-2)	
6.21	Bound. cond.	There is no suitable location for a connection, or the connection will be economically unfeasible.	
	Input options	No; Yes	
6.22	Bound. cond.	Gauge difference between tram and train systems.	
	Input options	No; Yes	

Note: Sub-criteria 6.19a & 6.19b form a single sub-criterion but are split up as the factor for penalty and bonus are not equal.

Criterion 7: Vehicle width

Vehicle width has implications on vehicle capacity and structure gauge. There are technical solutions to use vehicles narrower than 2.65m in class A and B systems, as was proven in Kassel (and to a similar extent in the Hoekse Lijn). However, the required gauntlet track solution is expensive and technically rather complicated. Therefore, a combination of narrow vehicles and class A and B implementation is treated as a boundary condition in the suitability scan.

Bonus points are awarded if the full tram corridor is fully suitable for 2.65m wide vehicles, or if a conversion can be done while upgrading street layouts. A large part of the penalty results from the amount of works required to accommodate wider vehicles as this increases the cost of the system. Some additional penalty follows when the platform gap for the existing fleet is widened, as this influences accessibility. If the current fleet has a high floor, a slightly increased platform gap is less of an issue compared to low-floor vehicles.

If there is no tram system in the investigated city (which follows from the quick scan), 5 points are awarded for criterion 7, which follows from complying with the baseline. It is eminent that a lot of works are required for a new tram line, but this is known beforehand when researching tram-train in such a city. Therefore, no penalty points are given.

Table 5-17: Implementation of criterion 7 in the suitability scan.

Crit.	Type	Description and input options	Factor
7.23	Baseline	Tram-train vehicles of desired width can be accommodated in the network.	
	Input options	No (0); Yes (5)	
7.24	Bonus	Tram corridor is already fully suitable for 2.65m vehicles.	1*
	Input options	No (0); Yes (2)	
7.25	Bonus	Modification of the corridor can be done in a street remodelling programme.	1*
	Input options	No (0); Partly (1) Completely (2)	
7.26	Penalty	Amount of ‘undesired’ works required to accommodate wider vehicles.	0.75
	Input options	A) None (0); B) Some (-1); C) Much (-2)	
7.27	Penalty	Platform gap for existing narrower fleet is increased on (parts of) the shared section, which results in reduced accessibility.	0.25
	Input options	No (0); Yes (-2)	
7.28	Bound. cond.	Tram-train vehicles of desired width cannot be used in the network.	
	Conditional	True if 7.23 is no	
7.29	Bound. cond.	Tram-train vehicles of less than 2.65m to be used in a class A/B system.	
	Input options	No; Yes	

* Both bonus conditions have a factor of 1, as they cannot be true simultaneously.

Criterion 8: Vehicle length

To provide sufficient transport capacity, it might be possible that the required tram-train vehicles are longer than current trams. The baseline, and boundary condition, is that the vehicles of the required length can be accommodated at the network, which might be impossible if there are very short track sections between intersections, or if using longer vehicles requires so much construction work that tram-train becomes economically or socially unacceptable. A bonus is awarded if there are no track works required at all. Also, the possibility of using 75m vehicles is awarded with a bonus, although of less weight than the former. On the other hand, if a lot of track work is required, this results in a penalty. A distinction is made between platform modifications and extensive rail works.

If there is no tram system in the investigated city (which follows from the quick scan), 5 points are awarded for criterion 8, which follows from complying with the baseline. The bonus for allowing long vehicles can still be awarded. It is eminent that a lot of works are required for a new tram line, but this is known beforehand when researching tram-train in such a city. Therefore, no penalty points are given.

Table 5-18: Implementation of criterion 8 in the suitability scan.

Crit.	Type	Description and input options	Factor
8.30	Baseline	Tram-train vehicles of desired length can be accommodated in the network.	
	Input options	No (0); Yes (5)	
8.31	Bonus	No track works required at all, tram-train vehicles have the same length as current trams.	0.80
	Input options	No (0); Yes (2)	
8.32	Bonus	Double traction/75m vehicles possible on the network.	0.20
	Input options	No (0); Yes (2)	
8.33	Penalty	Platforms must be extended for the tram-train vehicles.	0.5
	Input options	A) None (0); B) Some (-1); C) All along the corridor (-2)	
8.34	Penalty	Extensive track works required (switch relocations, modifications to track and street layout).	0.5
	Input options	A) None (0); B) Some (-1); C) Many (-2)	
8.35	Bound. cond.	Tram-train vehicles of desired length cannot be used on the tram network.	
	Conditional	True if 8.30 is no	

Criterion 9: Service quality of urban alignment

The right-of-way of the urban tram tracks define the service quality and reliability that a tram-train service can achieve. As a baseline, the amount of ROW B track is used. Vuchic (2007) notes that for LRT, 40% ROW B is typically the lower boundary. From a reliability perspective, 60% or higher is preferable. Vuchic also notes that ROW A alignment on busy sections can improve reliability. Therefore, the presence of ROW A is awarded at least 1 bonus point. The largest part of the penalty results from absence of priority to public transport on intersections, as this has a large influence on the reliability of a timetable. A small penalty is given to sections of pedestrian area. Although pedestrian area greatly reduces speed, this is also a destination area, and the reduced speed can be estimated. Furthermore, the presence of sections of ROW C and gauntlet track are penalised. The penalty depends on the length of the sections, rather than the combined length. Several short sections might cause less unreliability than a single long section. However, if the full alignment is ROW C, tram-train will probably not be able to provide reliable services, and in class A/B systems, this requires large slack at changeover points. In such cases, it is advised to keep the systems separated and improve transfer facilities.

Table 5-19: Implementation of criterion 9 in the suitability scan.

Crit.	Type	Description and input options	Factor
9.36	Baseline	Percentage of ROW A/B tracks.	
	Input options	p<40% (0); 40≤p<60% (2); 60≤p<80% (4); p≥80% (5)	
9.37	Bonus	Densely occupied sections are ROW A.	
	Input options	A) None (0); B) Some (1); C) Most (1.5); D) All (2)	
9.38	Penalty	Priority to public transport on intersections.	0.4
	Input options	No (-2); Yes (0)	
9.39	Penalty	Presence of pedestrian areas.	0.1
	Input options	A) None (0); B) Short sections (-1); C) Long sections (-2)	
9.40	Penalty	Presence of ROW C sections in busy traffic.	0.25
	Input options	A) None (0); B) Short sections (-1); C) Long sections (-2)	
9.41	Penalty	Presence of gauntlet track.	0.25
	Input options	A) None (0); B) Short sections (-1); C) Long sections (-2)	
9.42	Bound. cond.	City tracks are almost fully ROW C.	
	Input options	No; Yes	

Criterion 10: Frequency on tram network

The frequency on shared sections of tram tracks defines the offered frequency to passengers. At short headways, the reliability of services decreases (Teodorović & Janić, 2016). Especially for tram-train, the reliability is important. Several experts noted that a very high frequency on the shared section can be a serious issue. Therefore, for frequencies above 15 tph, the score decreases. Boundary conditions are that the frequency should be below 25 tph on ROW C and below 30 on ROW B.

Table 5-20: Implementation of criterion 10 in the suitability scan.

Crit.	Type	Description and input options
10.43	Baseline	What is the maximum frequency on a shared tram section?
	Input options	f≤3 tph (0); 4≤f≤5 (1); 6≤f<10 (3); 10≤f≤15 (5); 15<f≤20 (4); 20<f<25 (3); f≥25 tph (0)
10.44	Bound. cond.	Shared frequency 25 or more tph on ROW C alignment.
	Input options	No; Yes
10.45	Bound. cond.	Shared frequency 30 or more tph on ROW B alignment.
	Input options	No; Yes

Criterion 11: Service at main station and stabling capacity

Ideally, a tram-train service calls at a train platform at a main station. This way, easy transfer to other (long-distance) rail services can be offered. However, if tram-train is used to relieve station capacity, it is possible that the main station is served at a tram stop. This is much more desired than not serving the station at all, and therefore awarded 3 points. The quality of the transfer determines the penalty score, with walking distance as the most important component.

A bonus is awarded if there is stabling capacity at the station, which makes it possible to use double traction on the regional line, while using single vehicles on the city network.

Table 5-21: Implementation of criterion 11 in the suitability scan.

Crit.	Type	Description and input options	Factor
11.46	Baseline	Tram-train serves a long-distance railway hub.	
	Input options	A) No (0); B) At tram stop (3); C) At train platform (5)	
11.47	Bonus	There is stabling capacity at the main station yard or at the platform, which enables splitting and combining trains at the main station.	
	Input options	No (0); Yes (2)	
11.48	Penalty	Tram-train cannot be served within main station, transfers to other train services become more difficult; height component.	0.25
	Input options	A) No height difference (0); Height difference (-2)	
11.49	Penalty	Tram-train cannot be served within main station, transfers to other train services become more difficult; distance component.	0.5
	Input options	A) Less than 3 minutes' walk (0); B) Walk of 3 minutes or longer (-2)	
11.50	Penalty	Tram-train cannot be served within main station, transfers to other train services become more difficult; building component.	0.25
	Input options	A) Within same building (0); B) Not in same building, covered walk possible (-1); C) Not in same building, uncovered walk (-2)	

Criterion 12: Design speed of tram-train vehicle

The design speed of tram-train vehicles influences the travel time and the capacity consumption of tram-trains on heavy rail corridors. Although the achievable speed is also greatly dependent on the stop spacing, the design speed of vehicles is a more generic indicator. From a capacity point of view, it is beneficial if the maximum tram-train speed is equal to the line speed.

Table 5-22: Implementation of criterion 12 in the suitability scan.

Crit.	Type	Description and input options
12.51	Baseline	What is the design speed of the tram-train vehicle?
	Input options	v≤70 km/h (0); 70<v≤80 (1); 80<v≤100 (3); v>100 km/h (5)
12.52	Bonus	Is the vehicle design speed equal to the line speed?
	Input options	No (0); Yes (2)
12.53	Bound. cond.	Maximum speed too low for line length.
	Conditional	True if the line length (quick scan) > 35km and vehicle speed (12.51) < 100 km/h.

5.2.2.4 IV. Access and egress

It was found that adequate access and egress modes can support a public transport system. However, absence of these facilities will not necessarily mean that tram-train is not a suitable alternative. Therefore, the access and egress criteria have no boundary conditions.

Criterion 13: Bicycles

Cycling can increase the coverage of stops on both the access side (generally regional towns) and the egress side (within the city). On the access side, good facilities (i.e. sheltered and secured) for bicycle parking should be provided, while on the egress side, efficient public bike-sharing services can support tram-train. However, bicycles can also be a competitor to a public transport system on short distances.

Table 5-23: Implementation of criterion 13 in the suitability scan.

Crit.	Type	Description and input options	Factor
13.54	Baseline	A city's culture and topography support cycling as addition to public transport.	
	Input options	A) Not at all (0); B) Somewhat true (2.5); C) Very true (5)	
13.55	Bonus	Public bike-sharing facilities are readily available.	0.33
	Input options	A) No (0); B) At some large stops (1); C) At most stops / free floating service (2)	
13.56	Bonus	Good bicycle parking facilities at regional stations.	0.33
	Input options	A) No (0); B) At some stations (1); C) At most stations (2)	
13.57	Bonus	Bicycles may be taken on board tram-train service.	0.33
	Input options	No (0); Yes (2)	
13.58	Penalty	Distances in the city are short and bicycles are an important competitor to public transport in the city.	
	Input options	A) No (0); B) Somewhat true (-1); C) Very true (-2)	

Criterion 14: Public Transport

If regional public transport is coordinated with tram-train services at small regional nodes, the system becomes more attractive to people further out into the region. For them, the city centre becomes reachable within a single, efficient transfer. DRT and GRT can provide additional accessibility in small towns which are not fully covered by a stop.

Table 5-24: Implementation of criterion 14 in the suitability scan.

Crit.	Type	Description and input options
14.59	Baseline	Regional public transport is coordinated with the tram-train service.
	Input options	A) Not at all (0); B) Hourly or less than hourly (2.5); C) Twice per hour or more frequent (5)
14.60	Bonus	DRT or GRT available at some stops.
	Input options	No (0); Yes (2)

Criterion 15: Park and Ride

Park and Ride facilities motivate people to park their car at edges of cities or near regional stations and travel into the city by public transport. Tram-train can provide connections to parking areas further out a city. If the tram-train service also provides direct access towards long-distance railway hubs before entering the city tracks, it can serve as a satellite parking space for such a hub.

Table 5-25: Implementation of criterion 15 in the suitability scan.

Crit.	Type	Description and input options	Factor
15.61	Baseline	Park & Ride facilities can be provided in the tram-train scheme.	
	Input options	No (0); Yes (5)	
15.62	Bonus	P&R facilities are already offered at some regional stations.	0.5
	Input options	A) No (0); B) At some stations (1); C) At most stations (2)	
15.63	Bonus	Tram-train enables a P&R to be a satellite facility for a main railway hub.	0.5
	Input options	No (0); Yes (2)	

5.2.2.5 Conclusion on the included criteria

With the analysed criteria categories, a complete overview of the suitability of a tram-train corridor can be established. Categories I and IV (Population and structure; Access and egress) are corridor-specific criteria. When analysing a different regional corridor, it is likely that the scores of these criteria change. The criteria of category III (public transport network) are mostly related to the chosen route through the city. Lastly, the criteria of category II (relation between the urban region and the city) are generally applicable for the entire urban region and the most important when defining the suitability of tram-train. These criteria are most indicative of the original concept of tram-train; connecting settlements in the urban region directly to attraction centres in the city centre. The importance of the criteria of category II was also highlighted by the weights given to these criteria in the expert judgement sessions.

5.2.3 Suitability scan criteria 16-17: Demand analysis

A very rough capacity and frequency analysis can be made if a possible number of train paths is given in the quick scan. If class C/D is possible on track layout C-F, a minimum headway of three minutes (20 tph) is assumed, which is longer than minimum heavy rail headways (appendix A.6). A desired frequency and expected travel demand can be set as boundary conditions.

The vehicle capacity depends on the vehicle size. A maximum capacity of 500 passengers can be reached when 75m long vehicles with a width of 2.65m are used. For narrower vehicles, it was found that the capacity is around 10-15% lower (Figure 2-5). The potential vehicle capacity is determined according to Table 5-26, with the desired vehicle width according to user input. The vehicle length results from sub-criteria 8.32 and 11.47.

Table 5-26: Estimated vehicle capacity.

Desired vehicle width (Criterion 7)	Length (sub- criteria 8.32 and 11.47)	Resulting vehicle dimensions	Estimated capacity
< 2.65m	Both no	2.40m x 35m	225
2.65m	Both no	2.65m x 35m	250
< 2.65m	Either one yes	2.40m x 75m	450
2.65m	Either one yes	2.65m x 75m	500

Capacity is determined by equation (1), with the frequency resulting from the quick scan input, or set to 20 tph and the vehicle capacity resulting from Table 5-26. If the indicated capacity is lower than the expected demand, tram-train may not be able to provide sufficient transport capacity. Therefore, tram-train is not suggested as a suitable mode.

Furthermore, the desired frequency (for instance following from service quality demands) is tested against the possible frequency. If the possible frequency is lower than the desired frequency, tram-train is not a suitable mode.

5.2.4 Suitability

The suitability of tram-train is determined by determining in what range the end score of an analysed region lies. The suitability scan results in an end score, which is either 0 points for an analysis not complying with at least one of the boundary conditions, or somewhere between a minimum score of 17 points and a maximum score of 269 points. The values follow from the way the scoring (section 5.2.2) and weighing (Appendix E.1) were set up. Therefore, for understandability, the score is presented as a percentage of the maximum score.

The qualitative nature of the suitability scan might lead to inconsistent valuation of inputs (Triantaphyllou, 2000). It is decided to compensate for this by using fuzzy logic for the outcome, in which small transition zones between outcome ranges exist, rather than hard boundaries (Trillas & Eciolaza, 2015). The ranges and transition zones were estimated by taking the analysed reference systems into account. The end scores of most systems are relatively similar, ranging from 60 to 75%, with one system scoring significantly lower at 51%. Therefore, it was decided to use transition zones of 5% (13 points). When larger transition zones are used, it is expected that many analyses will result in an outcome in a transition zone. This reduces the distinction between the outcomes and thereby limits the value of the result as support to decision-making. An erroneous input due to inconsistency results in a base score error of at most 2 points (2-10 points after weighing). Therefore, the 5% (13 points) margin is expected to be sufficient to compensate for inconsistency or ambiguity of a few criteria.

In Appendix E.2, the results of the analysis of the reference lines are presented. Below, an interpretation of these outcomes is provided, based on which the ranges were established.

i. 0 - 40%: Tram-train is probably not a realistic alternative for the investigated corridor.
ii. 35 - 60%: Tram-train can probably be used in the investigated corridor but is not a very suitable alternative.
iii. 55 - 75%: Tram-train can be used in the investigated corridor and is a suitable alternative.
iv. > 70%: Tram-train can be used in the investigated corridor and is a very suitable alternative.

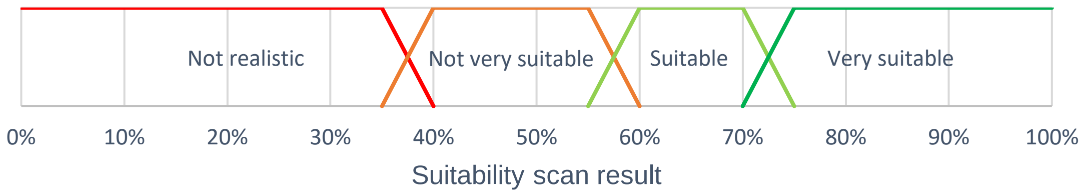


Figure 5-5: Visual representation of the suitability ranges.

Tram-train is not a realistic alternative

Two of the analysed reference systems do not meet all boundary conditions; Nordhausen and Nantes. In Nordhausen, narrower vehicles than 2.65m are used for a class A system. However, the system itself is an integration of a metre-gauge tramway and a metre-gauge railway. Therefore, the requirement of 2.65m wide vehicles is not a relevant boundary condition in this situation. The designed model is generalised towards standard gauge systems and cannot deal properly with this specific case.

In Nantes, the tram system was designed for trams with a width of 2.4m. The tram-train vehicles of 2.65m cannot be used on the urban network. It was chosen not to integrate the tram-train into the urban tram network. The suitability scan points out that tram-train is not a realistic alternative due to the vehicle width, which reflects the real situation.

Tram-train can be used, but is not very suitable

Not considering the aforementioned boundary condition, only the line in Nordhausen falls in this category. This is due to low scores on the regional characteristics and access and egress modes, which follow from the small population size of the corridor and city. The implementation of tram-train in Nordhausen was an opportunistic usage of the local situation, but the resulting service (hourly, low speed) is not of high quality.

Tram-train is suitable

In interviews (Van der Bijl, 2018; Kühn, 2018), it was learned that not all existing tram-train systems are successful or designed optimally, thus should be not be *very suitable*. For example, the line in Mulhouse does not draw the ridership that was initially expected. In cities which developed a tram-train network, tram-train is at least suitable. If the first tram-train line was unsuccessful, it is unlikely that a network would have been built.

A few pilot projects should fall into this category, such as Chemnitz C11, Sheffield and the RijnGouweLijn. In Sheffield, the project was used as a technical proof-of-concept within a relatively easy setting rather than a specific improvement to the public transport network (TAUT, 2017). As such, the line in Sheffield is in the transition zone between not very suitable and suitable. Similarly, the first line of the Chemnitz scheme was not the most suitable but proved successful and led to the construction of better lines (Kühn, 2018).

Tram-train is very suitable

Based on the reference lines, the minimum score for a very suitable system is determined to be 70%. Only a few lines fall into this category by base score. This category is mainly used to measure the effect of the sensitivity analysis, and to find distinct lines with a good chance of success.

5.2.5 Sensitivity analysis

The performed suitability scan, with weights based on expert judgement results in a generalised suitability. However, in section 2.2, several measures to achieve certain improvements were outlined. If the applicability of tram-train is researched with one of these specific improvements in mind, some criteria may be more important than in a general case. Also, sensitivity of stressed importance of cost is analysed. In the sensitivity analysis, some weights and scores are altered to see the effect on the suitability of tram-train. The results of the sensitivity scan are twofold. First, the end score is adjusted. This can improve the suitability range the analysed line lies in, relative to the initial maximum score. Secondly, the actual effect of the sensitivity analysis is compared to the maximum possible effect. If a line scores poorly on the analysed improvement objective, the increase in score will be limited compared to the maximum possible increase.

For all sensitivity analyses, it holds that they should be interpreted with care. The model provides a generalised indication, which might not be completely accurate for the considered region.

Line capacity

It was found that capacity depends on vehicle size and frequency. Therefore, when improving transport capacity is regarded as one of the main goals, the model is modified according to Table 5-27. With these modifications, vehicle size and possible frequency are stressed. In an optimal situation, the end score of an analysed region can be increased by 19.6 points (7.3%).

Table 5-27: Sensitivity analysis: line capacity.

Criterion		Modification
7	Vehicle width	Weight + 20%
8	Vehicle length	Weight + 50%
8.31	75m vehicles possible	1 additional bonus point awarded to criterion 8.
9, 10	Quality and frequency on tram network	Weight + 20%
10.43	Frequency on shared network	15-20 tph awarded 5 instead of 4 points.
11.47	Stabling possibility at main station	1 additional bonus point awarded to criterion 11.

Decreasing (experienced) travel time

Travel time follows from the time spend on the various steps of a trip, and benefits from a high level of reliability. The experienced travel time can be improved by removing transfers and providing enough capacity in vehicles. Therefore, when shortening travel times is the main reason to improve public transport, the model is modified according to Table 5-28. The maximum end score can be increased by 20.2 points (7.5%).

Table 5-28: Sensitivity analysis: travel time.

Criterion			Modification
5		Distance between station and attraction centre	Weight + 33%
9		Reliability of tram network	Weight + 25%
	10.42	Frequency on tram network	Baseline score for frequencies above 20tph reduced by 1 point.
	12.51	Vehicle speed	Score for speed of 100 km/h 4 instead of 3 points. Speeds above 100 km/h 6 points instead of 5 points.
13, 14		Cycling & regional PT	Weight + 20%

Improving network coverage

If achieving a high network coverage is desired, it should be assured that many passengers can reach a stop easily, and that attraction centres can easily be reached. Therefore, the restriction on housing density is removed and low and medium density have an increased score. Furthermore, the possibility of creating several corridors (both absolutely as the effectiveness of a connection) and the possibility of serving multiple attraction centres are increased in importance. Lastly, coordination with regional public transport is stressed. Cycling is not included in this sensitivity criterion, as cycling is not an accessible mode for PRM. The implementation of network coverage sensitivity is shown in Table 5-29. A maximum increase of 28.3 points (10.5%) can be achieved, when all relevant base scores are maximised. Network coverage is one of the strengths of tram-train, which is why the sensitivity has a larger influence.

Table 5-29: Sensitivity analysis: network coverage.

Criterion			Modification
1		Population density around stops	Very low density increased to 2 points. Low density increased to 4 points, medium density to 5. Weight + 20%
	1.3	Only very low-density housing	Boundary condition removed.
2		Multiple corridors possible	Weight + 25%
4		Served attraction centres	Bonus sub-criteria factors + 50% (bonus score [0, 3]). Weight + 20%
	6.19b	Effectiveness of connection	Bonus sub-criteria score C) 3 points.
14		Regional PT	Weight + 20%

Improving sustainability or attractiveness of public transport

It was found that rail modes are more sustainable and more attractive than bus transport. Therefore, when sustainability or attractiveness is regarded as driver for public transport improvements, the end score of the suitability scan is increased by 6.7 points (2.5%). The possible benefit of this sensitivity criterion is lower than for the other criteria because this sensitivity is not necessarily specific to tram-train but holds for light rail in general. Moreover, from the Maslow pyramid (Figure 2-2), it was learned that experience is a satisfier, contrary to speed and convenience, which are dissatisfiers. Therefore, only focussing on experience is less effective.

Cost

Several criteria have sub-criteria which are strongly cost-related. Therefore, if there is emphasis on the cost aspect of a tram-train scheme, modifications according to Table 5-30 are made to the model. Basically, if expected large cost drivers are present, the scores of these criteria are reduced to 0 points. Compared to an optimal case, the maximum score is reduced by 39 points (14.5%). Cost can be a very important decision criterion, so a large decrease in suitability can be justifiable. However, the outcome of the cost sensitivity analysis should always be considered in perspective. If only a very small network is affected, the sensitivity analysis need not be so decisive.

Table 5-30: Sensitivity analysis: cost.

Criterion		Modification
6.19	Effectiveness of the corridor	Sub-criterion scoring doubled
6.20	Connection between tram and train track at difficult location	If the connection will be difficult to build, the score of criterion 6 is reduced to 0 points.
7.26	Amount of track works	If works are required, the score of criterion 7 is reduced to 0 points.
8.33	Platform modifications	If 8.33 is C, the score of criterion 8 is reduced to 0 points.
8.34	Amount of track works.	If works are required, the score of criterion 8 is reduced to 0 points.
7.26, 8.34		If 7.26 and 8.34 are both C), then tram-train is not advised.

5.3 Verification of the models

To prove that the models represent reality, their results are verified. This is done by inserting the data of the systems analysed in 4.2, as well as the system around the city of Saarbrucken. The case of Saarbrucken was not used during the development of the model, which makes it a valuable verification case, due to the absence of any relation to the model source data.

5.3.1 Quick scan

In the verification process of the quick scan, it is analysed whether the outcome class and mode of the quick scan resembles the real situation. Table 5-31 shows the result of the verification process. In the table, the real-world implementation is listed, as well as the outcome of the quick scan. The last column (overall) indicates whether the scan has the correct result (✓), gives an incorrect possible implementation (~), or indicates that no possible implementation exists (*X*).

Table 5-31: Verification results quick scan.

System/Line	Real-world	Separate criteria	Outcome class	Outcome mode	Remarks	Overall
Karlsruhe S1-S	C – Main	Yes	A / C	Main	Limited frequency.	✓
Karlsruhe S1-N	C – Main	Yes	A / C	Main	Limited frequency.	✓
Karlsruhe S4	C – Main	Yes	C	Main	Limited frequency. Corridor unsuitable for class A/B.	✓
Karlsruhe S5-W	A – Main	No – Corridor	A	Main	Too short for a single line.	*X*
Karlsruhe S5-E	A – Main	Yes	A	Main / Sec		✓
Karlsruhe S51	A – Main	Yes	-	Main	Corridor unsuitable for class A/B; Heavy rail usage restricts class C/D.	*X*
Karlsruhe S52	A – Main	Yes	A / B	Main	Class B unlikely. Limited frequency.	✓
Karlsruhe S7	A – Sec	Yes	-	Main / Sec	Corridor long (49 km) Corridor unsuitable for class A/B; Heavy rail usage restricts class C/D.	*X*
Karlsruhe S8	A – Main	No – Corridor	-	Main / Sec	Corridor too long (56 km). Corridor unsuitable for class A/B; Heavy rail usage restricts class C/D.	*X*
Kassel RT1	A – Main	Yes	A	Main		✓
Kassel RT4	A – Sec	Yes	A	Main / Sec	Limited frequency	✓

System/Line	Real-world	Separate criteria	Outcome class	Outcome mode	Remarks	Overall
Kassel RT5	A – Sec	Yes	A	Main	Population spread confines to main mode. Spread type D can be argued; this results in secondary as possible mode.	~
Chemnitz C11	C – Main	Yes	A / C	Main	Limited frequency	✓
Chemnitz C13	A – Main	Yes	A	Main	Limited frequency	✓
Chemnitz C14	A – Main	Yes	A	Main		✓
Chemnitz C15	A – Main	Yes	A	Main		✓
Nordhausen	A – Main	No – City	A	Main	City too small.	X
Mulhouse	A – Main	Yes	A / B	Main	Limited frequency	✓
Nantes T1	D – Main	No – Corridor	C / D	Main	Corridor too long (58 km) Limited frequency	X
Nantes T2	B – Main	Yes	A / B	Main		✓
Sheffield	A – Sec	No – Corridor	-	Secondary	Too large population per line km; Too short corridor.	X
RijnGouwelijn	None (B – Main)	No - Corridor	-	Main	Too large population per line km; Corridor unsuitable for class A/B.	~
Cádiz	B – Main	No - Corridor	-	Main	Too large population per line km.	X
Paris T4	D - Feeder	Yes	D	Feeder		✓
Saarbrucken-S	B – Main	Yes	B	Main		✓
Saarbrucken-N	B – Main	Yes	B	Main		✓

5.3.1.1 Discussion of incorrect results

- *Karlsruhe S5-West:* This corridor is marked as too short by the quick scan. In practice, the section is a connection between Karlsruhe and Wörth, via a large heavy railway bridge over the river Rhine. In Wörth, the line continues as tramway. Due to the river Rhine, an extension of the tram network, which would have been the advised alternative, would be very expensive. Besides, the connection is also used for other, longer corridors. The quick scan does not take this opportunity into account. In the suitability scan (criterion 2), the possibility of implementing multiple corridors is treated. After the verification process, this criterion is included into the quick scan, and fed forward into the suitability scan. Table 5-5 is adjusted into Table 5-32.

Table 5-32: Implication of corridor length – updated after verification.

Corridor length	Tram-train implementation
0-10 km	Possible as feeder service or when part of a longer corridor. Otherwise it is advised to extend the urban tram network.
11-35 km	Optimal length.
36-50 km	Suboptimal, a high speed should be realised to offer competitive travel times.
> 50 km	No-go, too long to offer attractive services.

- *Karlsruhe S51:* Line S51 was used as data point to determine the population per line km frontier for class A and B and therefore, class A and B should be possible. However, due to rounding while approximating the frontier, the data point of line S51 has fallen just above the possible area.

- *Karlsruhe S7:* Line S7 is long (49 km), runs partly as a class C line and partly as a class A line. As mentioned before, line S7 might be (partly) transformed back into a heavy rail line, which indicates that the model outcome is not necessarily incorrect.
- *Karlsruhe S8:* Line S8 is very long (56 km), which results in very long trip times (74 minutes from the Albtalbahnhof, the border between tram and train). As with S7, it was noted that line S8 might be transformed back into a heavy rail line in the future. Again, this indicates that the model result is not necessarily incorrect. Line S8 is mostly a class C line, except for a very short section through the Rastatt station. It is questionable whether the population per line km frontier of class A/B lines is applicable in these situations.
- *Kassel RT5:* Population spread type B was used in the verification process, which seems the most suitable, but eliminates the possibility of secondary mode. In practice, it is arguable whether the spread type is B or D. Choosing spread D leads to the possibility of using secondary mode. This indicates both an issue with interpretation of the spreads (clear guidelines should be provided), and raises the question whether population spread type B should also allow for implementation of secondary mode. Secondary mode can be of added value when there is sufficient transport demand, or significant travel time improvements can be achieved. Therefore, secondary mode is unlikely to be useful for short corridors with low population.
- *Nordhausen:* In Nordhausen, opportunistic use was made of the existing metre-gauge tramway and metre-gauge heavy railway. As a pragmatic modelling approach was used, and cities below 100K are regarded as too small for tramways, it was expected that Nordhausen would be rejected by the quick scan.
- *Nantes T1:* In Nantes, a railway line was remodelled into a tram-train to benefit from tram operation on a city section, and from the higher train speed on the regional section. Although this is a sensible approach, the implemented solution is not connected to the urban network, and therefore does not provide seamless travel into the city. The resulting line resembles a typical railway, which is not captured by the model.
- *Sheffield:* The line between Sheffield and Rotherham was used as a pilot for British organisations to learn from. The situation in Sheffield was suitable for a technical and operational pilot (a lightly used railway line, close to the tram network), but it can be argued whether tram-train is the most suitable for the corridor. Nevertheless, the model does not reproduce what was implemented, because it cannot deal with the large populations of two separate cities, which are also located very near each other.
- *RijnGouwelijn*: This project was cancelled before it was implemented. The corridor population is too high for tram-train when Gouda is included in the corridor. When Gouda is excluded, the corridor is still too high for class A/B implementation. However, it is difficult to determine the focus city for parts of the corridor. If, for the line between Alphen and Leiden only half the population of Alphen is considered, a tram-train between Alphen and Leiden would be possible (Class B, main mode, resembling the original idea).
- *Cádiz:* Verification with the case of Cádiz revealed two issues. First, it was difficult to define the core city and the region. Cádiz is the core city but has no tram network and a tram line was constructed in the other cities. This approach is inverted from the general concept and highlights the flexibility of tram-train. However, the model cannot deal with this. Secondly, the population along the corridor exceeds the set maximum value. As with the Sheffield case, the model is not able to deal with the large populations of the three cities.

5.3.1.2 Conclusion

The quick scan works well for regions with a main city and less urbanised surrounding and is able to produce accurate results. However, the model has difficulties with compound lines (e.g. partly class A, partly class C). Compound lines are difficult to generalise, as their composition is very location-specific. Secondly, the model performs poorly for heavily urbanised regions (Sheffield, RijnGouweLijn, Cádiz). Most implementations of tram-train serve a relation between a less densely populated region and a main city. The class A/B frontier and maximum density along the corridor were estimated for such regions, because of the limited data for heavily populated areas. It is probable that for short, heavily populated corridors the frontier and upper boundary have a different behaviour than for longer regional corridors. Unfortunately, there is too little data available to reliably estimate such values. On the other hand, for heavily urbanised regions, it is also possible that inter-city transport flows either exceed the possible absolute capacity of class A/B tram-train or have too little inter-city demand to justify investments for tram-train next to existing (rail) modes.

5.3.2 Suitability scan

The outcomes of the systems analysed in section 4.2 were used to determine the suitability scores. The city of Saarbrucken, which was used as a non-dependent verification case for the quick scan is used again to verify the suitability scan.

According to expert judgement, the line around Saarbrucken is suitable, but not very suitable. The rationale is that the line required two connections and although the inner-city section was specifically built for tram-train, it does not directly serve all relevant attraction centres, such as the university. The two half lines have been analysed separately, and both parts score well in the suitable region. Thus, the scan provides an accurate result for Saarbrucken.

The suitability scan was also tried for the tram-train of Cádiz. As was noticed while verifying the quick scan, the difficulty of determining the city and region around Cádiz was an issue while trying the quick scan. It was not possible to use the suitability scan for this area.

5.3.2.1 Criteria

Dodgson et al. (2009) note that redundant criteria should be omitted from an MCA. Therefore, a frequency analysis was performed on the fifteen included criteria. There is no main criterion on which all systems score the same, which indicates that all criteria have some impact on the end score. A similar analysis was performed on the sub-criteria. Here, it turns out all systems have the same score for sub-criterion 5.15. Therefore, it is doubted whether the sub-criterion is relevant and should be included. However, it is decided not to remove the sub-criterion based on this small data set.

It was found that in several cities, the frequency on the tram network is more than 20 tph. In the suitability scan, the maximum score is awarded for 10 – 15 tph, with decreasing scores for frequencies up to 25 tph. Above 25 tph, no points are awarded. However, such high frequencies need not directly result in a very unreliable timetable and are penalised too much. Therefore, the scoring of criterion 10.43 (Table 5-20) is changed into:

$$f \leq 3 \text{ tph } (0);\ 4 \leq f \leq 5\ (1);\ 6 \leq f < 10\ (3);\ 10 \leq f \leq 20\ (5);\ 20 < f < 25\ (4);\ f \geq 25 \text{ tph } (2)$$

Taking into account the weight, this modification increased the score of several reference lines by 2 points, except for Kassel RT1 and RT4, which were increased by 4 points. For Karlsruhe line S52 and Kassel line RT4, the modification also leads to an improved suitability range. Both lines have a new score of 70%, which is just within the very suitable region. Moreover, the modification has a minimal effect on the sensitivity analysis for line capacity.

Several criteria are prone to different interpretations of input values, which results from the qualitative aspect of the data. Some margin for this is included in the overlap between the ranges, but this can influence the scoring. Iteratively, the input values were defined as much as possible. The impact can be reduced further with clear guidelines for the input categories.

One of the advantages of tram-train is the possibility to bypass main stations or even bypass detours around a city, by using tram-tracks directly towards attraction centres. However, such lines are likely not able to provide (fast) connections to a main station. This possibility was overlooked when developing the model. The advantage of a solution with a ‘bypass’ through the city can be a disadvantage when tram-train is implemented as main mode in a region where there is a strong demand for transport towards the main station. Not serving the main station is already penalised via criteria 6.18 and 11. Therefore, the bypass can be added as a separate criterion as a Likert-scale, where the possibility and desirability of such a line is valued.

5.3.2.2 Sensitivity analysis

In Kassel, the tram-train scheme was developed to enable people from the region to travel into the city centre more easily (NVV, 2006). Therefore, the main objective was to extend the network coverage. Table 5-33 shows the result of the sensitivity analysis for the region of Kassel. The sensitivity analysis indicates that tram-train is well able to provide the desired improvement and therefore is a very suitable alternative. The sensitivity analysis performs as desired.

Table 5-33: Sensitivity analysis of the Kassel RegioTram.

Line	Initial score	Initial outcome	Score after sensitivity analysis	Outcome after sensitivity analysis
RT1	184.7 (69%)	Suitable	207.7 (77%)	Very suitable
RT4	187.7 (70%)	Suitable	210.7 (78%)	Very suitable
RT5	201.8 (75%)	Very suitable	228.8 (85%)	Very suitable

5.3.2.3 Conclusion

The suitability scan provides an additional indicator of the likeliness of tram-train being implemented successfully in an urban region. However, as with the quick scan, it is important to have a clear distinction between the region, where tram-train operates as a train, and the city, where tram-train operates as a tram. The criteria included in the model provide a representative indication of the suitability, although a relevant criterion on possible bypass routes was not included. It was found that the way the criteria were developed could lead to inconsistencies in inputs. This is partly corrected for by the overlap in suitability ranges but can best be prevented by defining clear guidelines on what each input category includes.

5.4 Feasibility of technical integration

One of the large disadvantages of tram-train is the technical difference between the two modes. Getting two separate systems to work together requires thorough engineering. Additionally, most cities have their own systems and technical specifications, so no general technical solution for tram-train yet exists. However, lessons can be learned from implemented and failed projects. These lessons are captured in a library of technical integration issues and solutions, which can be used as a checklist when determining technical feasibility. This section describes the development of the integration and assessment framework, which are used to organise the library. The library with the assessed solutions is provided in appendix F.

5.4.1 Integration framework

Rail-bound public transport consists of three components: rolling stock, infrastructure and operational aspects. In this framework, operational aspects include actions required by drivers, responsibility and to some extent planning. Figure 5-6 shows the three system components and their relation. Between the components, there are interfaces. Properly aligned interfaces between the components ensure that a system can be operated at all, and that operations are efficient. An example of the interface between infrastructure and rolling stock is track gauge: vehicles with an axle width of 1000mm cannot operate on standard gauge track, which is 1435mm wide. Similarly, designing infrastructure for 300km/h, while not implementing a cab signalled train protection system is a mismatch between infrastructure and operational aspects. Using a vehicle without any form of train protection on this system results in an unmatched interface between the three components.

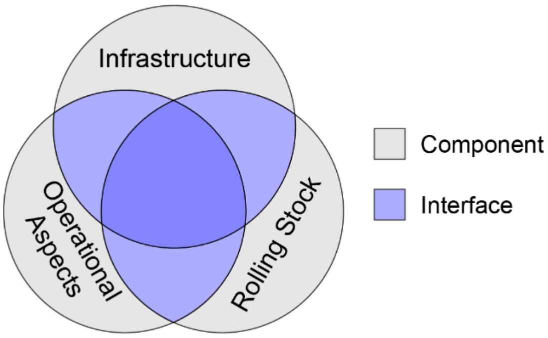


Figure 5-6: Components of rail-bound systems and their interfaces.

For existing systems, such as urban trams or heavy railways, the interfaces of the components have been specified and aligned. For tram-train systems however, a new issue arises: two full systems should be aligned. This is visualised in Figure 5-7, where the separate tram and train systems have been positioned above each other. The interfaces on the top and bottom planes have been aligned already – these are the existing systems. However, new interfaces arise in an intermediate plane, vertically between the components of the two systems. Table 5-34 lists all interfaces on the three planes.

Table 5-34: Overview of all interfaces in tram, train and tram-train systems.

Internal interfaces – Tram	Tram-train interface	Internal interfaces - Train
Rolling Stock – Infrastructure	Rolling Stock – Rolling Stock	Rolling Stock – Infrastructure
Rolling Stock – Operational Aspects	Rolling Stock – Infrastructure	Rolling Stock – Operational Aspects
Infrastructure – Operational Aspects	Rolling Stock – Operational Aspects	Infrastructure – Operational Aspects
Rolling Stock, Infrastructure & Operational Aspects	Infrastructure – Infrastructure	Rolling Stock, Infrastructure & Operational Aspects
	Infrastructure – Operational Aspects	
	Operational Aspects – Operational Aspects	
	Rolling Stock, Infrastructure & Operational Aspects	

For tram-train, it is widely accepted that regular trams cannot be used on the train lines, mainly due to the rolling stock – rolling stock interface. Therefore, special tram-train vehicles have been designed to solve that interface. Essentially, this creates an additional plane with only the rolling stock component in the 3D-scheme, but this is difficult to visualise. However, the additional plane leads to an extension of the list of tram-train interfaces:

- Rolling stock (tram-train) – Rolling stock (tram)
- Rolling stock (tram-train) – Rolling stock (train)
- Rolling stock (tram-train) – Infrastructure (tram)
- Rolling stock (tram-train) – Infrastructure (train)
- Rolling stock (tram-train) – Operational aspects (tram)
- Rolling stock (tram-train) – Operational aspects (train)
- Infrastructure (tram) – Infrastructure (train)
- Infrastructure (tram) – Operational aspects (train)
- Infrastructure (train) – Operational aspects (tram)
- Operational aspects (tram) – Operational aspects (train)
- Rolling stock (tram-train) - Infrastructure (either type) - Operational aspects (either type)

As tram-train vehicles are generally derivatives of tram vehicles, the interfaces between tram-train vehicles and the tram rolling stock, infrastructure and operations will likely not have many issues. Considering this and for pragmatic reasons, the library is categorised in the seven main interfaces as listed in Table 5-34, rather than the more extensive list. Figure 5-8 provides an indication of possible interface issues between tram and train systems and the relevant sections of the technical solution library.

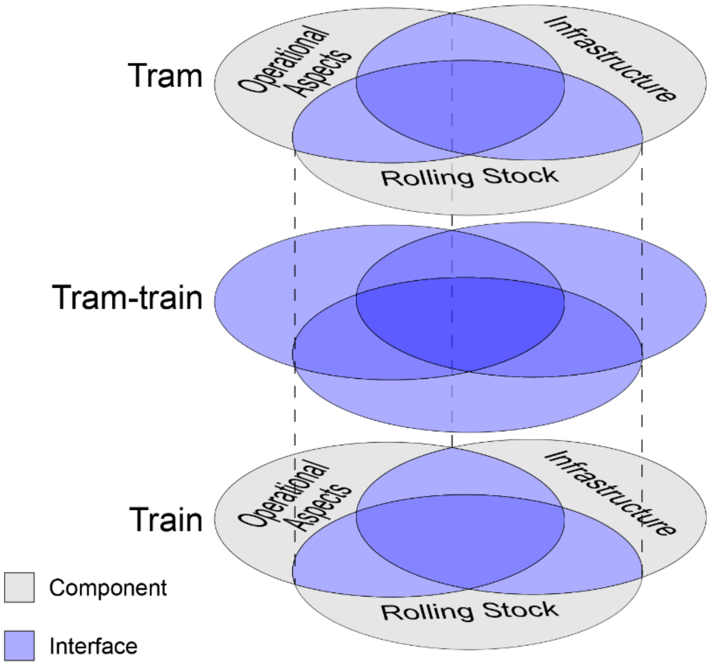
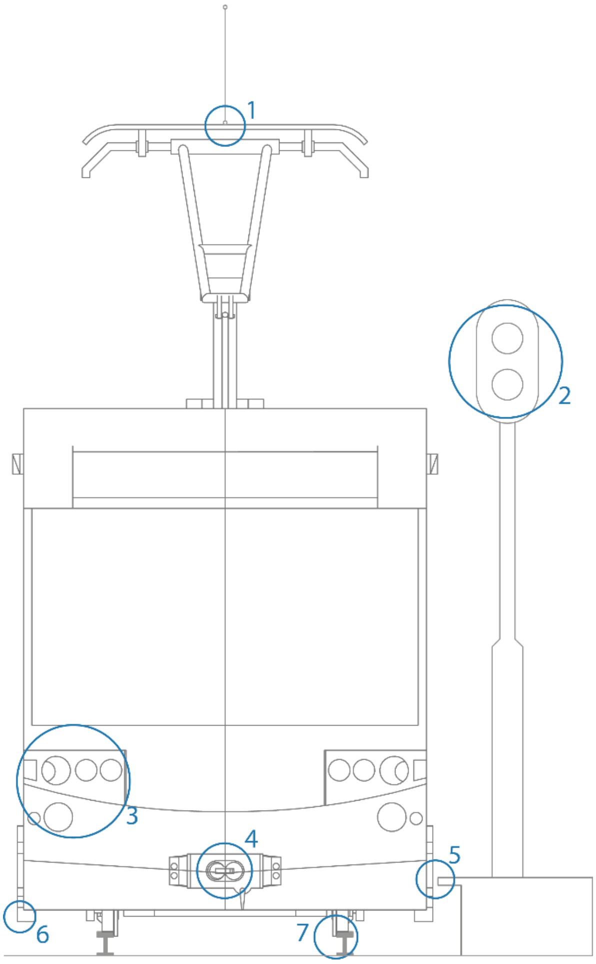


Figure 5-7: Interfaces resulting from integration of tram and train.



1. Power supply (F.2.4) & Pantograph – overhead line interface (F.2.10)
2. Signalling system (F.2.2; F.6.2)
3. Vehicle lights (F.6.3)
4. Passive safety (F.1.1)
5. Vehicle – platform interface (F.2.3)
6. Loading & structure gauge (F.2.8)
7. Wheel-rail interface (F.2.6)

Figure 5-8: Indication of possible interface issues.

5.4.2 Assessment of suitability and implication of certain implementations

In existing tram-train systems, many issues with interfaces between the tram and train system have been solved. However, some solutions are specific to local conditions, and might not be useful in other situations. The solutions to issues with interfaces will be assessed qualitatively on their impacts on:

- Cost;
- Operational parameters;
- Existing rolling stock;
- New rolling stock (tram-train vehicles);
- Rail infrastructure (tracks and systems);
- Stations.

The assessment is based whether there is no impact (○), a small impact (●) or a large impact (●●) on certain criteria, compared to a reference scenario. For some criteria, a category of very large impact (●●●) is used to indicate solutions which have enormous impact on cost, existing rolling stock or rail infrastructure. When a solution has no impact on both rolling stock types, no distinction between the two categories is made. A similar approach is used when there is no impact on rail infrastructure and stations. An overview of the assessment framework, including reference scenarios, is provided in Table 5-35. In some cases, there can be impact on civil works (such as tunnels or bridges). This will be noted separately in the corresponding tables. The results of this analysis will be implemented in the designed tool. Where possible, based on parameters of the existing systems, a preferred solution will be provided.

The assessments can be used as reference when a tram-train system is designed, or to gain an insight in the possible impacts on the existing systems when tram-train is studied.

Table 5-35: Assessment criteria for technical solutions.

	○	●	●●	●●●
Cost *Reference: not implementing the solution.*	Not more expensive than the reference situation.	A small increase in cost compared to the reference. E.g. small modifications to a limited number of vehicles or a small section of infrastructure.	A large increase in cost compared to the reference. E.g. both rolling stock and infrastructure need to be modified.	A very large increase in cost compared to the reference. E.g. very extensive infrastructural modifications required.
Operations (planning, capacity/speed, procedures, human factors) *Reference: existing operations.*	No impact on operations.	Small impact on operations.	Large impact on operations.	*Not applicable*
Rolling stock (existing) *Reference: no modifications to existing rolling stock (train / tram) required.*	No modifications to existing rolling stock need to be made.	A small modification (e.g. retrofit) should be made to a limited number of vehicles.	A small modification should be made to a large/complete fleet of vehicles, or a large modification should be made to a limited number of vehicles.	A large modification should be made to a large/complete fleet of vehicles.
Rolling stock (new) *Reference: a regular urban tram.*	A reference vehicle can be used without modification.	A small modification should be made to a reference vehicle.	A large modification should be made to a reference vehicle.	*Not applicable*
Rail infrastructure *Reference: no modifications to infrastructure.*	No modifications to the rail infrastructure need to be made.	Small modifications should be made to the rail infrastructure.	Large modifications should be made to a small part of the rail infrastructure.	A large modification should be made to the full corridor (e.g. new signalling system).
Stations *Reference: no modifications to infrastructure.*	No modifications to the stations required.	Small modifications to stations required (e.g. remodelling of a platform).	Large changes to stations required (e.g. layout changes, new platforms).	*Not applicable*

For certain interfaces, legal requirements exist. For train operations, there are European Technical Specifications for Interoperability (TSI), which aim at standardising certain parameters throughout Europe. Besides the TSI, countries can have their own frameworks for railway and tram operations, the National Technical Rules (Godziejewski, 2018). It should always be investigated whether solutions can be implemented within such frameworks.

5.4.3 Determining relevant interfaces

For certain implementation classes, resulting from the quick scan, some interfaces do not occur. For class C and D lines, without mixed operation on the heavy rail parts, there is no interface between train and tram-train rolling stock. Some internal interfaces for train systems disappear as well, such as the interface between heavy rail infrastructure and trains. This enables operators and IMs to adjust the existing heavy rail infrastructure to the tram-train vehicles. Similarly, for class B and D implementations, some internal interfaces of tram systems need not be addressed due to the absence of regular tram rolling stock. Table 5-36 indicates the relevant interfaces for each implementation class. It is visible that for class A, all interfaces should be considered. For class D, a lot of interfaces are eliminated.

Depending on local conditions, certain components of interfaces might not exist. For instance, if there are no level crossings on the proposed corridor, the issue of passive safety on level crossings (F.2.1) is not relevant.

Table 5-36: Interfaces for the various classes. White: A, B, C, D. Blue: A, C. Green: A, B.

Internal interfaces – Tram	Combined interfaces	Internal interfaces - Train
Rolling Stock – Infrastructure	Rolling Stock – Rolling Stock*	Rolling Stock – Infrastructure
Rolling Stock – Operational Aspects	Rolling Stock – Infrastructure	Rolling Stock – Operational Aspects
Infrastructure – Operational Aspects	Rolling Stock – Operational Aspects	Infrastructure – Operational Aspects
Rolling Stock, Infra & Operational Aspects	Infrastructure – Infrastructure	Rolling Stock, Infra & Operational Aspects
	Infrastructure – Operational Aspects	
	Operational Aspects – Operational Aspects	
	Rolling Stock, Infra & Operational Aspects	

* For class C, the complicated rolling stock interface between tram-train and trains is removed, but the interface between tram and tram-train persists. However, this interface will generally not raise specific issues.

5.5 Conclusion

In this chapter, a three-step approach to determining the possibility and suitability of tram-train for an urbanised region was developed. The first two steps, the quick scan and the suitability scan are based on the criteria found in chapter 4.

The first step, the quick scan, determines the actual possibility of the various tram-train classes. A rough quantitative analysis of the population, infrastructure and heavy rail usage results in overall possibility of tram-train, and what classes and modes can be used. The developed model provides accurate results for regions with a clear main city and less populated surrounding but is considerably less usable in regions with larger corridor populations. For heavily urbanised regions, there was too little data available to find substantiated relations.

Secondly, in the suitability scan, it is analysed whether the city and rail transport network characteristics provide enough solution space for a tram-train solution. The analysis is based on several criteria, which collectively give an impression of the suitability of tram-train as a solution for a region. While verifying the model, it was found that it is most applicable for regions with a main city. For cities without a clear main city and surrounding region, the required inputs are difficult to determine.

Lastly, a framework for systematic identification of interfaces between tram and train systems was developed, with which a library of interface issues was created. Some of the interface issues are points to which attention should be paid, while for other issues multiple solutions were identified and assessed qualitatively. The library can be used as a reference when taking further steps towards the implementation of tram-train, such as a detailed feasibility study. Overall, there are no technical issues which are generally unsolvable. However, a tram-train system should be optimised locally, based on local conditions of the systems. Some interface issues might not be solvable locally due to limitations such as available space. In these cases, tram-train is technically unfeasible.

6 Development of the Tram-Train Implementation Support Tool

This chapter describes the development of a decision support tool, the Tram-Train Integration Support Tool (T-TIST). The T-TIST is based on the developed model and should implement this in an easy and understandable way. Most importantly, the T-TIST should provide a comprehensible overview of the results. In this chapter, the requirements and the design of the tool are outlined.

6.1 Requirements

To be able to construct a usable tool, it is important to specify the requirements.

The tool:

- ***Should include the models developed in chapter 5.*** This is the main specification.
- ***Should be able to indicate the relevant interfaces of the technical solution library.*** The solution library itself is added as an appendix to the tool.
- ***Should be easy to use by the targeted audience.*** The tool is mainly aimed at transport engineers within consultancy companies but should also be useable by transport authorities and municipalities. The tool is positioned in a very early project phase; therefore, it should be easy to acquire data and the results should be provided quickly.
- ***Should provide comprehensible results.*** The output of the tool should be easily understandable. Therefore, it should be visible what aspects define the output.
- ***Should be easily adaptable.*** Future lessons learned and additional studies (e.g. into class C systems) should be easily implementable in the tool.

6.2 Tool design

The T-TIST is constructed in Microsoft Excel and implements and automates the decision schemes of the quick scan and the multi-criteria analysis of the suitability scan. Furthermore, the T-T-TIST indicates the relevant technical interfaces based on the quick scan result. In the T-TIST, the layout of cells gives a clear overview of where users should provide inputs. At each input box, a brief indication of the required input data (numerical, category) is provided. While verifying the model, it was found that several input variables can be prone to inconsistent inputs due to interpretation differences. Although some of these issues were iteratively improved, some remain reliant on the interpretation. Therefore, a manual is provided with the tool, with clear descriptions of the various input values. The manual is provided in appendix G.

The output is presented directly per scan. Different inputs have a direct effect on the output, which provides an insight in certain options one might be investigating.

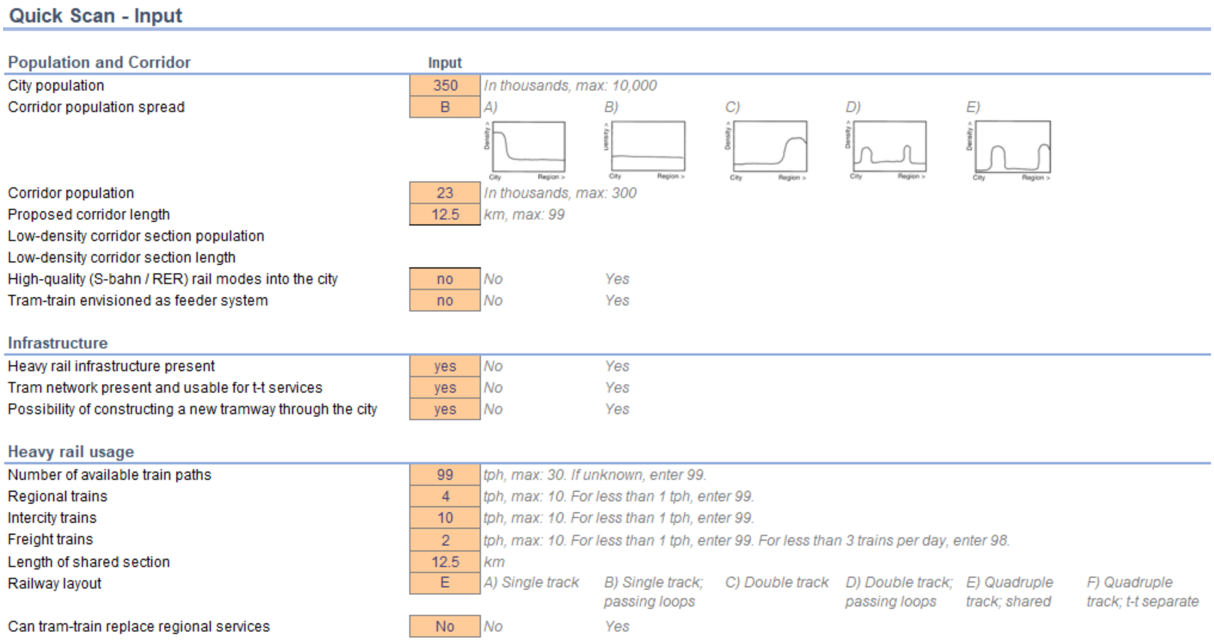
6.2.1 Quick scan

In the quick scan part of the T-TIST, the output should indicate whether tram-train is possible at all, and if so, what classes and modes can be used. For this, the tool completes Table 5-1 and

Table 5-2 automatically. The tool shows whether tram-train is possible for each separate criterion, indicates the possible classes and modes, and provides some additional information. This information can include the unlikeliness of certain classes, or the probability of tram-train only being able to offer a limited frequency. Moreover, the T-TIST indicates the position of the analysed corridor relative to the class A/B frontier, the overall population threshold and the line length threshold. Figure 6-2 gives an impression of the output of the T-TIST Quick scan. The provided graph is supportive to the scan outcome and helps users to interpret the (im-)possibility of tram-train regarding the population per line-km, as this indicator is not as straightforward as for instance line length. Table 6-1 lists the required inputs for the quick scan, distributed over the three main criteria. Figure 6-1 gives an impression of the implementation of this table in the T-TIST.

Table 6-1: T-TIST input variables.

Input variable	Input value	Notes
Population and corridor		
City population	Number of inhabitants in thousands	The population of the main city.
Corridor population	Number of inhabitants in thousands	The population of the settlements with stations along the proposed corridor. Neighbourhoods of the main city need not be included.
Corridor population spread type	Type A – E	Type according to Table 4-3.
Corridor length	Km	The track length of the proposed corridor, starting from the changeover between tram and train.
Low-density section population	Number of inhabitants in thousands	The total population of the settlements along the low-density section of the corridor; relevant for spread type A and C.
Low-density section length	Km	The length of the low-density section of the corridor; relevant for spread type A and C.
Presence of high-quality rail modes along corridor	Yes / no	Are there high-quality rail modes along the corridor, into the city (metro; S-bahn/RER)?
Line envisioned as feeder	Yes / no	Will the proposed line serve as a feeder to higher-level modes?
Infrastructure		
Heavy rail infrastructure present	Yes / no	Is there heavy rail infrastructure present along the proposed corridor?
Tram infrastructure present and usable	Yes / no	Is there a tram network in the city, and is this usable for the tram-train?
Possibility of constructing a new tram line	Yes / no	Is it acceptable to construct a complete new tram line for the tram-train
Heavy rail usage		
Number of available train paths	Trains per hour per direction	Should be filled out if known.
Regional trains	Trains per hour per direction	An indication of the current usage by regional trains should be given.
Intercity trains	Trains per hour per direction	An indication of the current usage by intercity trains should be given.
Freight trains	Trains per hour per direction	An indication of the current usage by freight trains should be given.
Can tram-train replace regional trains	Yes / no	Can the tram-train service replace the present regional rail service. If yes is selected, the frequency of regional services is set to 0.
Railway layout	Type A – F	Type according to Table 5-7.
Length of shared section	Km	The length of the section which is shared by the tram-train corridor and heavy rail services. This value can deviate from the corridor length when parts of the section will be used for tram-train only. This figure, however, cannot exceed the corridor length.



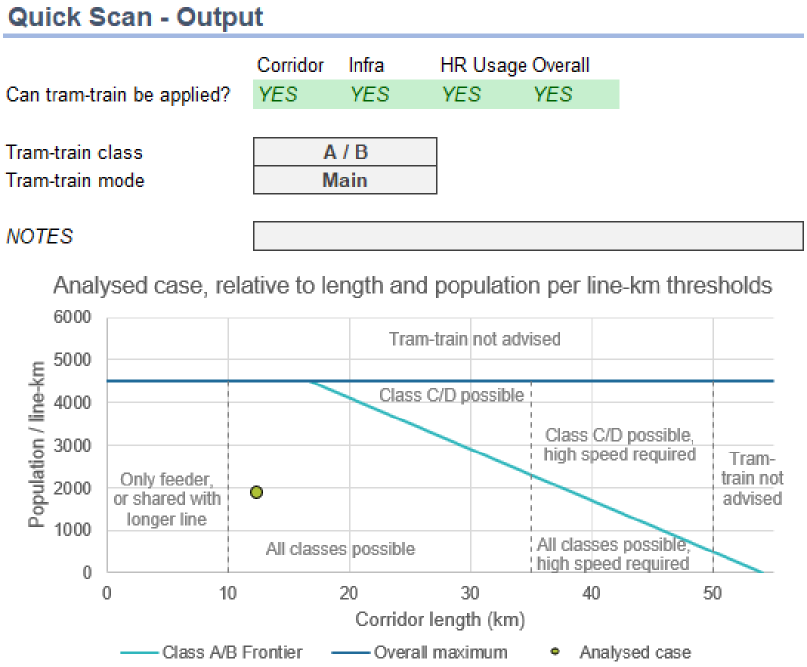
Quick Scan - Input

Population and Corridor	Input						
City population	350	*In thousands, max: 10,000*					
Corridor population spread	B	*A)*	*B)*	*C)*	*D)*	*E)*	
Corridor population	23	*In thousands, max: 300*					
Proposed corridor length	12.5	*km, max: 99*					
Low-density corridor section population							
Low-density corridor section length							
High-quality (S-bahn / RER) rail modes into the city	no	*No*	*Yes*				
Tram-train envisioned as feeder system	no	*No*	*Yes*				

Infrastructure							
Heavy rail infrastructure present	yes	*No*	*Yes*				
Tram network present and usable for t-t services	yes	*No*	*Yes*				
Possibility of constructing a new tramway through the city	yes	*No*	*Yes*				

Heavy rail usage							
Number of available train paths	99	*tph, max: 30. If unknown, enter 99.*					
Regional trains	4	*tph, max: 10. For less than 1 tph, enter 99.*					
Intercity trains	10	*tph, max: 10. For less than 1 tph, enter 99.*					
Freight trains	2	*tph, max: 10. For less than 1 tph, enter 99. For less than 3 trains per day, enter 98.*					
Length of shared section	12.5	*km*					
Railway layout	E	*A) Single track*	*B) Single track; passing loops*	*C) Double track*	*D) Double track; passing loops*	*E) Quadruple track; shared*	*F) Quadruple track; t-t separate*
Can tram-train replace regional services	No	*No*	*Yes*				

Figure 6-1: T-TIST Quick scan input screen.



Quick Scan - Output

	Corridor	Infra	HR Usage	Overall
Can tram-train be applied?	*YES*	*YES*	*YES*	*YES*

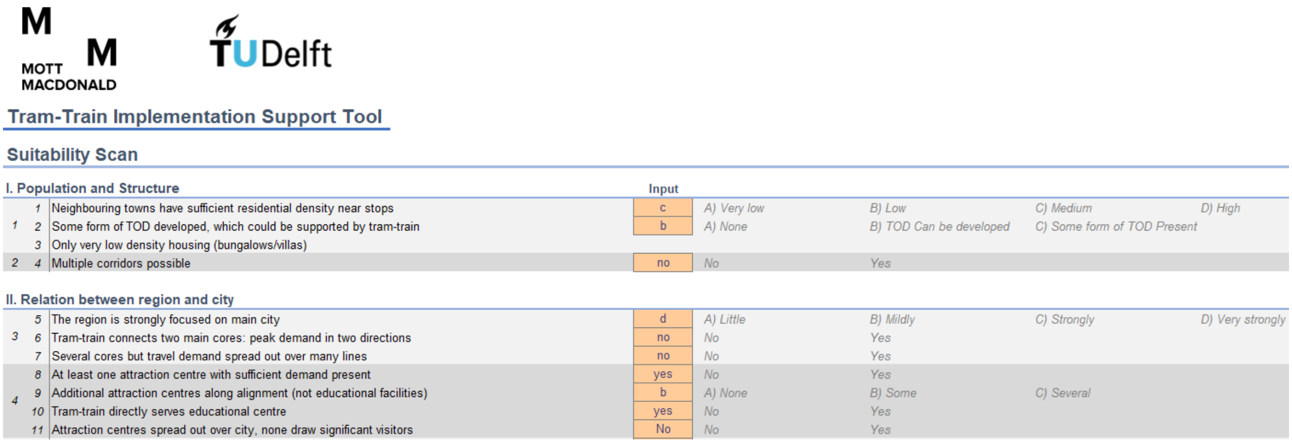
Tram-train class	**A / B**
Tram-train mode	**Main**

NOTES

Figure 6-2: T-TIST Quick scan output screen.

6.2.2 Suitability scan

The required input variables for the MCA part of the suitability scan have been discussed in section 5.2.2, and are entered into the tool as such. The tool provides brief guidance on possible inputs, but a more detailed description is provided in the manual. The tool transfers inputs that were already given in the quick scan automatically to the suitability scan. Figure 6-3 gives an impression of an input window for the suitability scan.



Tram-Train Implementation Support Tool

Suitability Scan

I. Population and Structure

			Input				
1	1	Neighbouring towns have sufficient residential density near stops	c	A) Very low	B) Low	C) Medium	D) High
	2	Some form of TOD developed, which could be supported by tram-train	b	A) None	B) TOD Can be developed	C) Some form of TOD Present	
	3	Only very low density housing (bungalows/villas)					
2	4	Multiple corridors possible	no	No	Yes		

II. Relation between region and city

3	5	The region is strongly focused on main city	d	A) Little	B) Mildly	C) Strongly	D) Very strongly
	6	Tram-train connects two main cores: peak demand in two directions	no	No	Yes		
	7	Several cores but travel demand spread out over many lines	no	No	Yes		
4	8	At least one attraction centre with sufficient demand present	yes	No	Yes		
	9	Additional attraction centres along alignment (not educational facilities)	b	A) None	B) Some	C) Several	
	10	Tram-train directly serves educational centre	yes	No	Yes		
	11	Attraction centres spread out over city, none draw significant visitors	No	No	Yes		

Figure 6-3: T-TIST Suitability scan input screen (excerpt).

For the capacity estimation, the potential frequency is imported from the quick scan, which is either the inputted number of available train paths or an estimation for class C / D. A frequency override function is available, which can be used to test the effect of different frequencies. The T-TIST estimates vehicle capacity as described in Table 5-26, but this figure can be overridden by the user.

The suitability range is determined based on the end percentage. This value is supported in the tool by providing the separate scores for the four criteria categories, as well as a graphical representation of the score per criterion including the effect of the bonus and penalty factors. This indicates why a region is (un)suitable. A user can use this information to find out what could be improved to increase the suitability. By altering the input values, the tool provides direct feedback on the effect of the changes. Figure 6-4 shows the output window of the T-TIST.

6.2.3 Inclusion of the technical scan

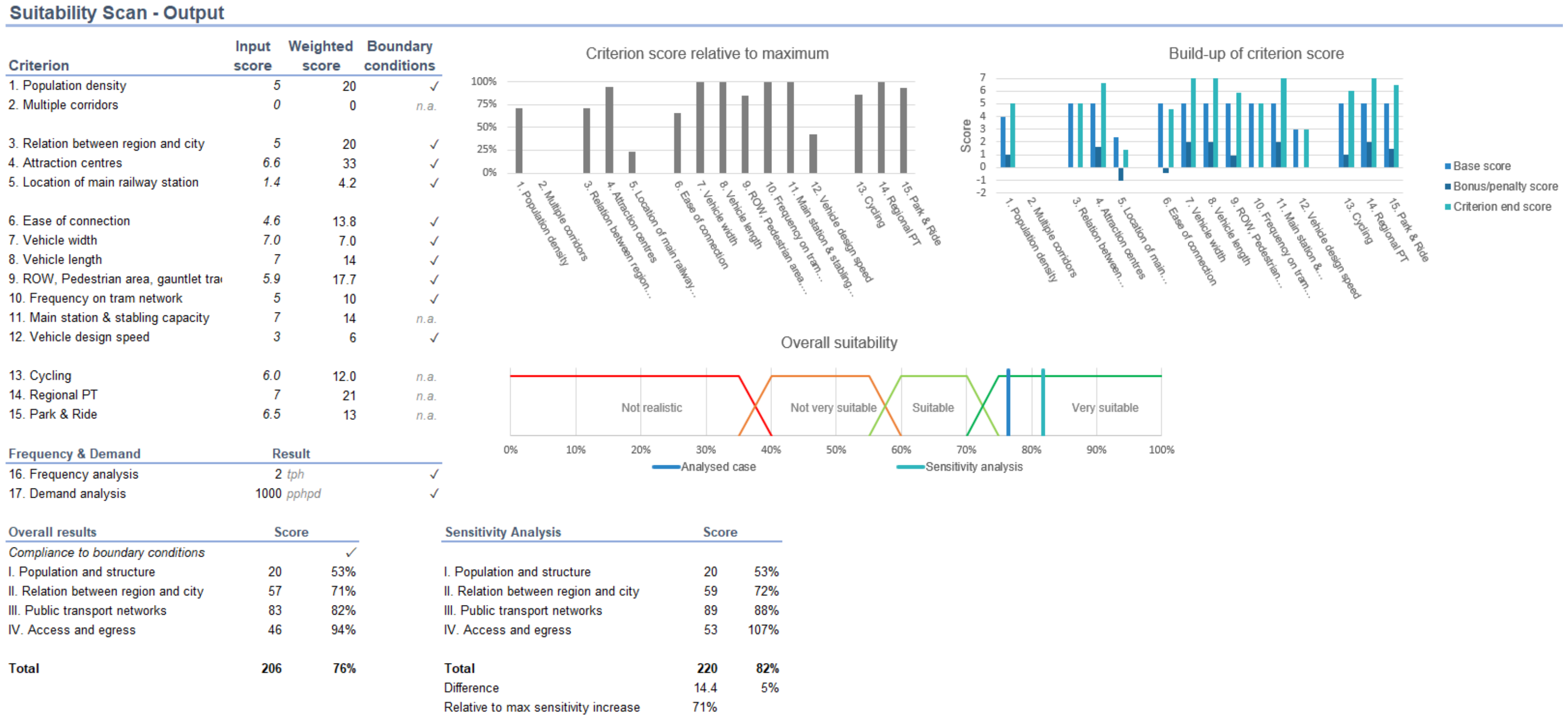
The technical library, as created in appendix F, is included in the T-TIST as well. The tool displays a comprehensive list of all relevant interfaces. Depending on the resulting class from the quick scan, some interfaces and solutions are not relevant. Therefore, these are not shown on the list, according to Table 5-36.

6.3 Conclusion

This chapter presents the implementation of the three model steps developed in chapter 5 into the Tram-Train Integration Support Tool. The tool can be used in early stages of public transport projects, when the objectives for the improvement have been defined and solution directions are researched. The tool requires easily obtainable inputs and provides results quickly.

The output screens of the quick scan and suitability scan give the important information in a single window. The numerical results are supported by graphical representations of the output, which improves the comprehensibility of the results. The implementation of the technical scan is limited, but the solution library can be included in later upgrades of the tool.

Overall, the designed T-TIST meets the set requirements. The usability of the T-TIST is evaluated in the next chapter.



Suitability Scan - Output

Criterion	Input score	Weighted score	Boundary conditions
1. Population density	5	20	✓
2. Multiple corridors	0	0	n.a.
3. Relation between region and city	5	20	✓
4. Attraction centres	6.6	33	✓
5. Location of main railway station	1.4	4.2	✓
6. Ease of connection	4.6	13.8	✓
7. Vehicle width	7.0	7.0	✓
8. Vehicle length	7	14	✓
9. ROW, Pedestrian area, gauntlet tra	5.9	17.7	✓
10. Frequency on tram network	5	10	✓
11. Main station & stabling capacity	7	14	n.a.
12. Vehicle design speed	3	6	✓
13. Cycling	6.0	12.0	n.a.
14. Regional PT	7	21	n.a.
15. Park & Ride	6.5	13	n.a.

Frequency & Demand	Result	
16. Frequency analysis	2 tph	✓
17. Demand analysis	1000 pphpd	✓

Overall results	Score	
Compliance to boundary conditions		✓
I. Population and structure	20	53%
II. Relation between region and city	57	71%
III. Public transport networks	83	82%
IV. Access and egress	46	94%
Total	**206**	**76%**

Sensitivity Analysis	Score	
I. Population and structure	20	53%
II. Relation between region and city	59	72%
III. Public transport networks	89	88%
IV. Access and egress	53	107%
Total	**220**	**82%**
Difference	14.4	5%
Relative to max sensitivity increase	71%	

Figure 6-4: T-TIST Suitability scan output screen.

7 Case studies

In this chapter, two case studies around the Dutch city of Utrecht are performed to see how well the designed T-TIST functions. The city of Utrecht (350,000 inhabitants (2018)), in the centre of The Netherlands, is used to test the T-TIST. The city has a large attraction on the surrounding region, where several smaller villages are located, and Utrecht Central Station (CS) is the main node in the Dutch railway network, with connections in many directions.

The case studies are used to evaluate the T-TIST on two criteria:

- **Usability:** Is the tool easy to use, and are the results easy to interpret?
- **Reliability:** Are the results sensible? This is evaluated by critical judgement of the result and supported by travel time calculations. The travel time calculation indicates what tram-train can ultimately bring the passenger.

7.1 Baarn - Utrecht

First, a corridor between Utrecht and Baarn is analysed. For this line, a new tramway should be constructed between the central station of Utrecht and the Maliebaan railway, a very lightly used railway through the city, where the tram-train could serve two new stations. Then, the line merges onto the busy railway between Utrecht and Amersfoort and passes through the towns of Bilthoven and Den Dolder, where two additional stations might be opened. Then, the line would branch off into Soest, serve the existing stations and finally serve the town of Baarn. Alternatively, a new tramway in Utrecht could connect the Maliebaan railway with the Uithoflijn, which serves the Utrecht Science Park (USP), a large attraction zone with several faculties of the University of Utrecht, the academic hospital and several companies. Figure 7-2 gives an overview of the full line and a close-up of the proposed inner-city alternatives. Table 7-1 shows the input for the T-TIST Quick scan.

Table 7-1: Quick scan input for Baarn - Utrecht.

Input variable	Input value	Notes
Population and corridor		
City population	350 thousand	
Corridor population	97 thousand	Bilthoven 22k; Den Dolder 4k; Soest 46k; Baarn 25k.
Corridor population spread type	Type C	Together, Baarn and Soest are significantly larger than Bilthoven and Den Dolder.
Corridor length	20 km	
Low-density section population	26 thousand	Bilthoven and Den Dolder are regarded as the low-density part of the corridor.
Low-density section length	8 km	
Presence of high-quality rail modes along corridor.	No	Around Utrecht, a network of high-quality regional trains was developed, but this is focused on transporting people to the main station.
Line envisioned as feeder	No	
Infrastructure		
Heavy rail infrastructure present	Yes	
Tram infrastructure present and usable	Yes	For the route towards the main station, existing tram infrastructure need not be used.
Possibility of constructing a new tram line	Yes	

Input variable	Input value	Notes
Heavy rail usage		
Number of available train paths	Unknown	
Regional trains	2 + 2 per hour	2 travel the full line and can be replaced. 2 use the shared section and cannot be replaced.
Intercity trains	4 per hour	
Freight trains	1 per hour	
Can tram-train replace regional trains	Yes	Tram-train can replace the regional services through Baarn and Soest.
Railway layout	C	Triple tracks. However, this requires trains to wait and cannot be used in two directions simultaneously.
Length of shared section	8 km	As the tram-train replaces some regional services, the shared section is limited to 8 kilometres.

First, the quick scan is performed. Figure 7-3 displays the output of the T-TIST for the inputs according to Table 7-1. The T-TIST indicates that tram-train is not possible for the analysed line, as the corridor conditions are unsuitable for any implementation. Therefore, the T-TIST cannot determine an implementable class and mode. The outputted graph shows that the servable population per line-km (4850 inh/km) exceeds the threshold of 4500 inh/km, as well as the class A/B frontier. In the analysis, the full population of Baarn and Soest is related to Utrecht. However, Soest and Baarn are closer to Amersfoort, with Baarn having a direct train connection to Amersfoort. For this specific corridor, it can be considered not to relate the entire population of Soest and Baarn to Utrecht, but also partly to Amersfoort. Under the assumption that two-third of the population of Soest and Baarn is related to Utrecht, the corridor population is reduced to 73 thousand inhabitants (3667 inh/km). The T-TIST output (Figure 7-4) shows that class A or B tram-train can be implemented as main mode. However, the T-TIST also notes that the current heavy rail usage on the 8 km of track layout C likely only permits a limited tram-train frequency.

In Soest the alignment consists of single track with one passing facility, and the replacement of regional services by tram-train along the proposed route will lead to the station of Utrecht Overvecht losing two hourly services. Although tram-train is not directly impossible, there are constraints to both the corridor and heavy rail usage. The limited frequency limits the possible capacity, which might be problematic for the relatively densely populated corridor. As a result, tram-train is probably not a realistic solution for the corridor. It is decided not to continue to the suitability scan. Figure 7-1 indicates the end of the case study in the analysis process.

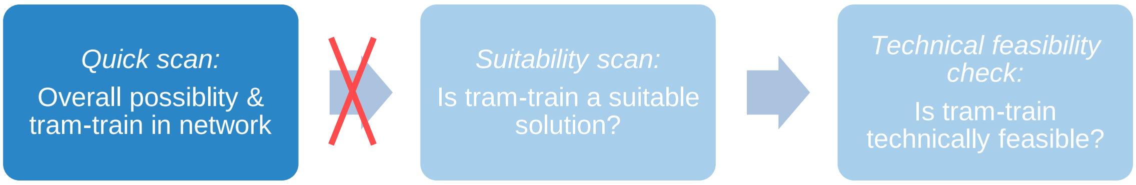


Figure 7-1: End of the analysis of Baarn - Utrecht after the quick scan.

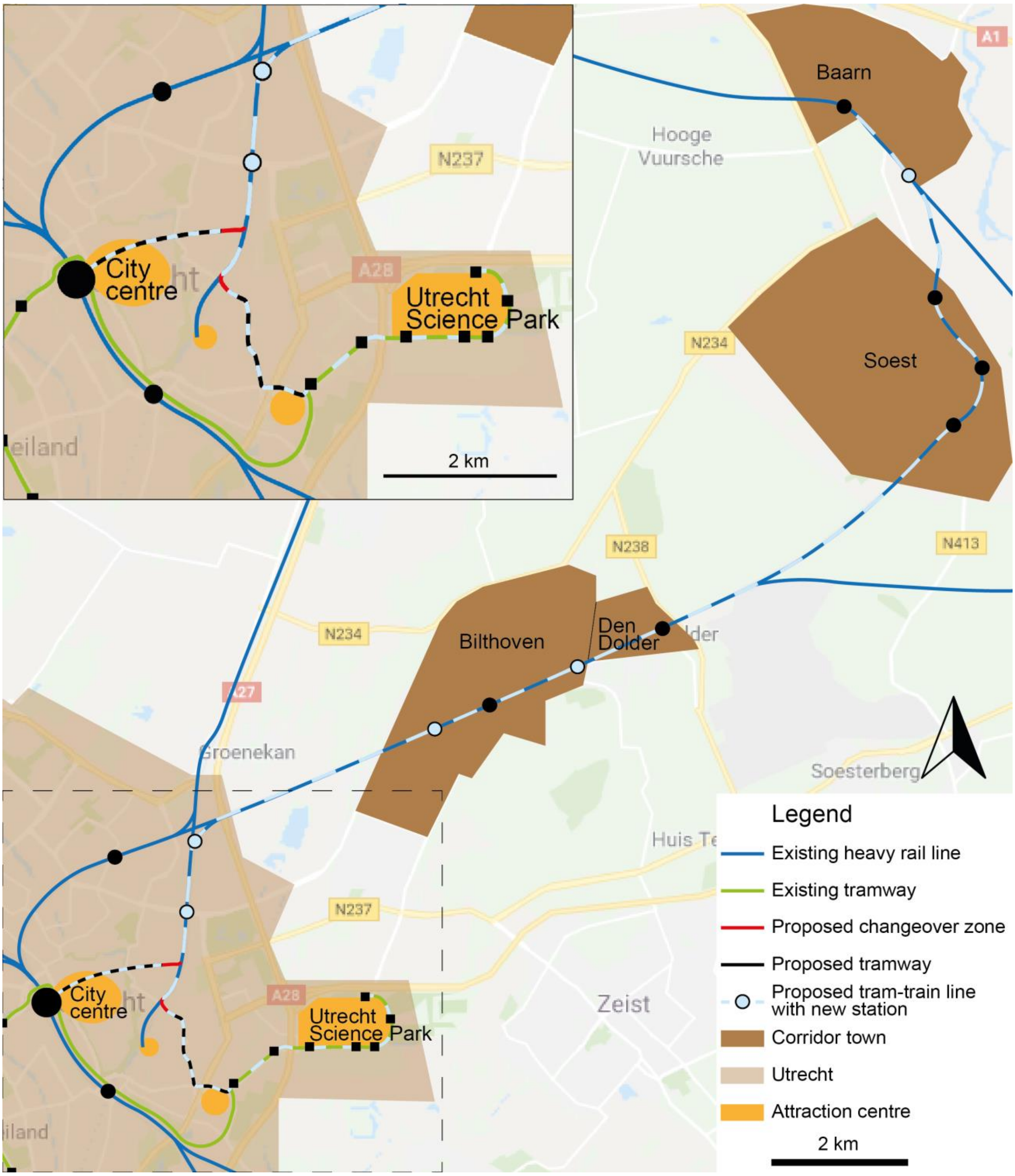
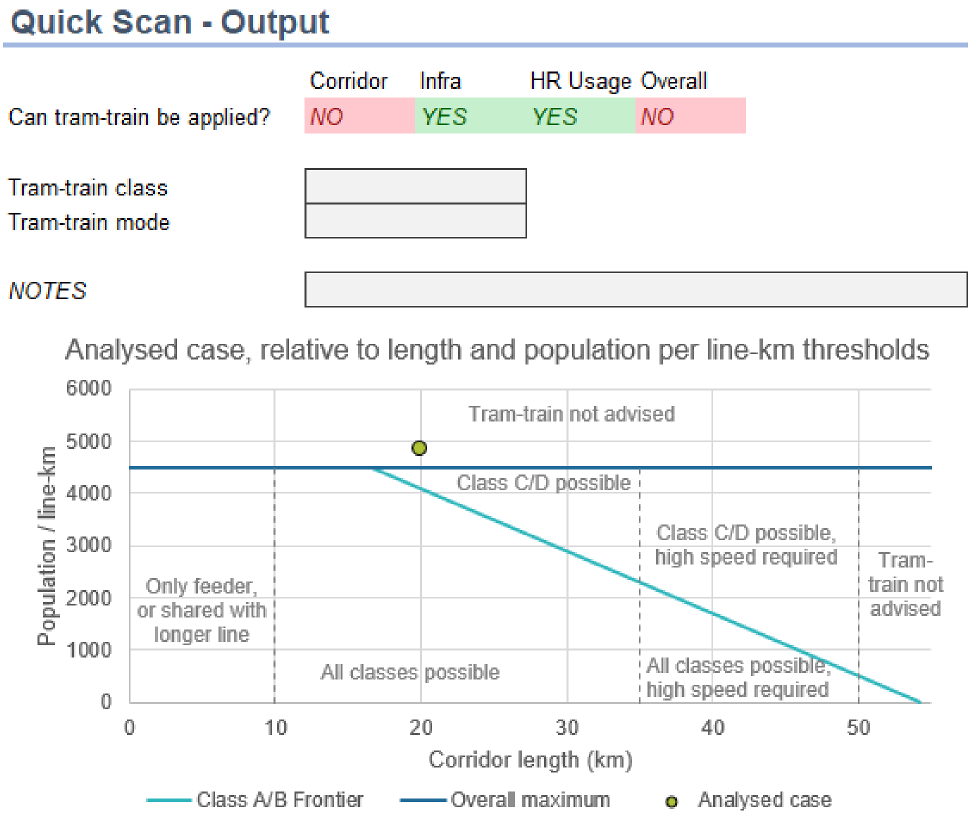


Figure 7-2: Baarn - Utrecht. Background: Google Maps.



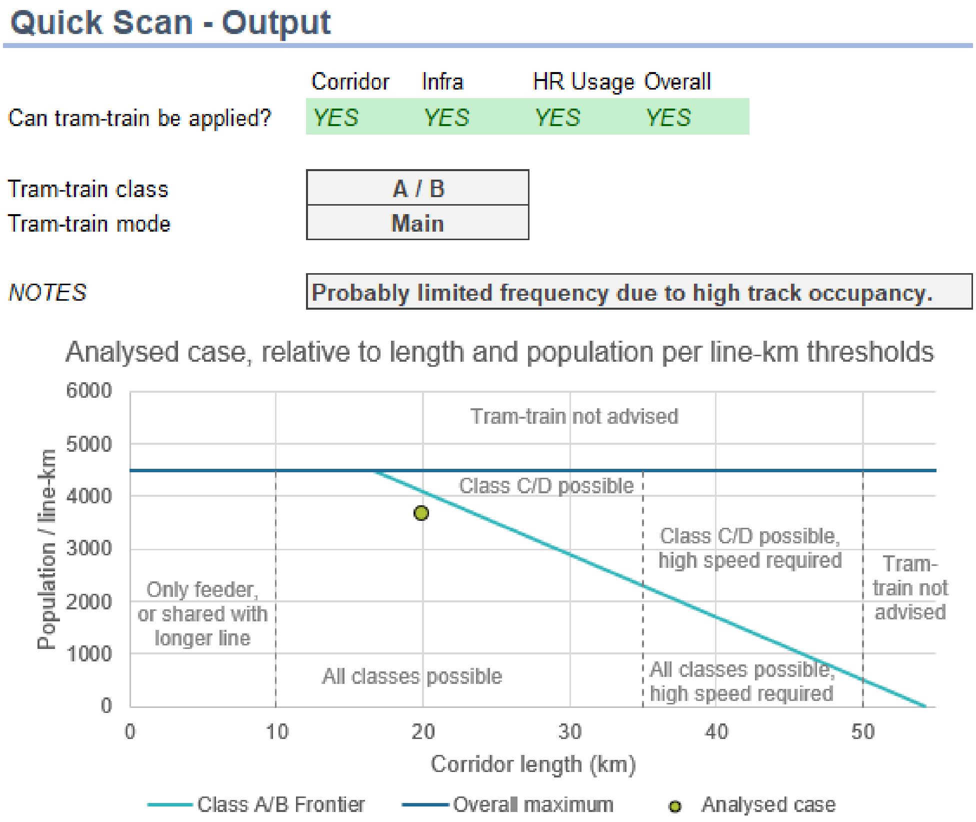
Quick Scan - Output

	Corridor	Infra	HR Usage	Overall
Can tram-train be applied?	*NO*	*YES*	*YES*	*NO*

Tram-train class	
Tram-train mode	

NOTES

Figure 7-3: T-TIST output for Baarn - Utrecht.



Quick Scan - Output

	Corridor	Infra	HR Usage	Overall
Can tram-train be applied?	*YES*	*YES*	*YES*	*YES*

Tram-train class	**A / B**
Tram-train mode	**Main**

NOTES **Probably limited frequency due to high track occupancy.**

Figure 7-4: T-TIST output for Baarn - Utrecht, after reconsidering the related population.

7.2 Breukelen - Utrecht

Although tram-train is probably not a realistic solution for the corridor between Utrecht and Baarn, a different corridor around Utrecht was analysed: Utrecht – Breukelen. Contrary to the first analysed corridor, the line to Breukelen will only serve two small towns: Maarssen and Breukelen. In Maarssen, two additional stations can be opened. Figure 7-5 gives an overview of the proposed line.

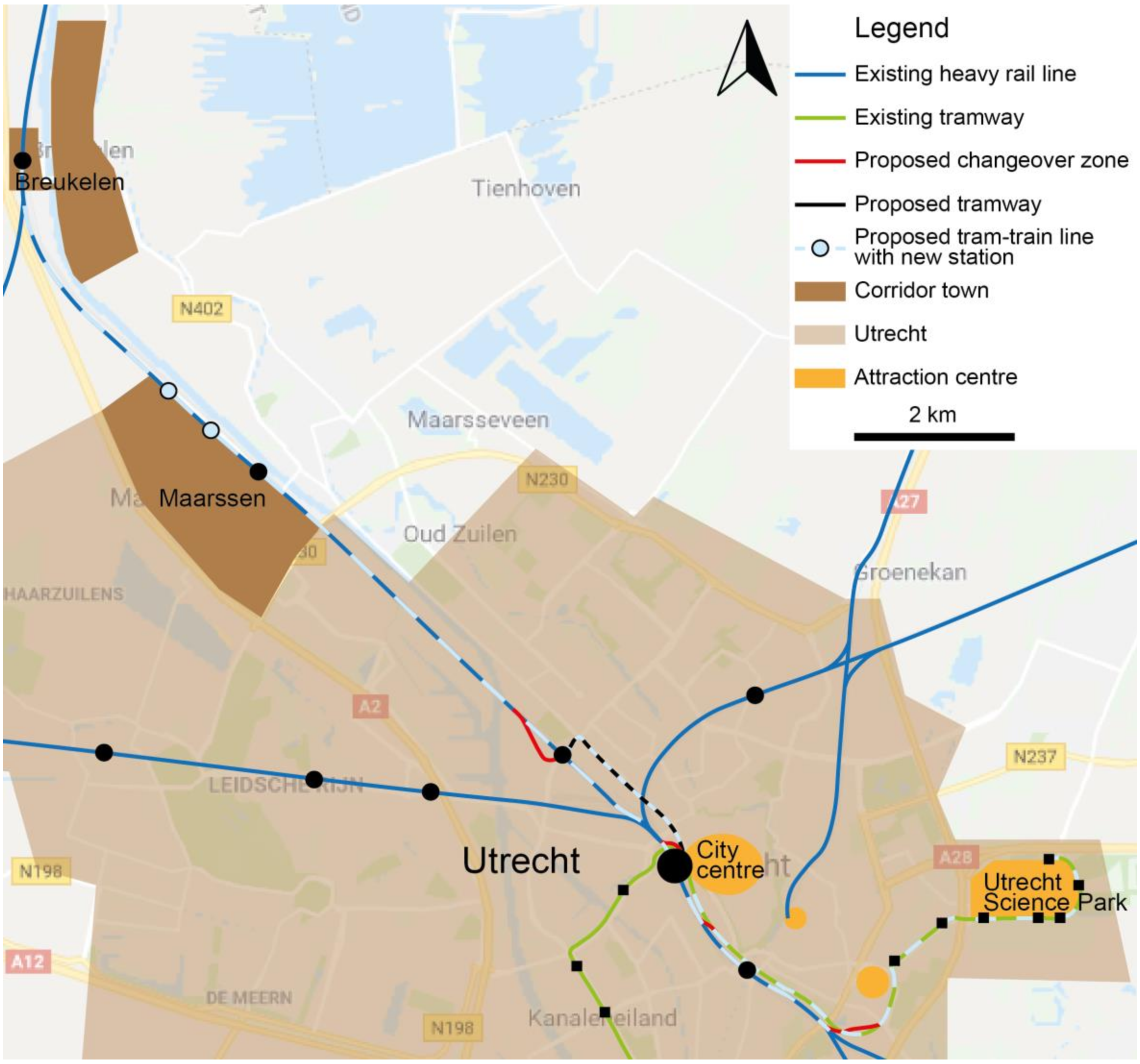


Figure 7-5: Breukelen – Utrecht Science Park; overview. Background: Google Maps.

Within Utrecht, the line can be connected to the existing Uithoflijn, towards the Utrecht Science Park. For this connection, four possibilities are identified, which are shown in Figure 7-6.

- Modification of Utrecht Zuilen into a tram stop, below the train tracks. A new tramway is to be constructed towards the main station of Utrecht, which benefits the catchment area of the line.
- A connection next to the main station. Space is relatively limited, but an overpass over the yard could provide a connection to the tram tracks.
- A connection between Utrecht Central Station and Utrecht Vaartsche Rijn. The tram tracks are next to the railway yard.

- A connection after Vaartsche Rijn. This connection is easier to construct, as it is not on the main yard of Utrecht CS, but the tram-train will spend more time on the heavily occupied train network.

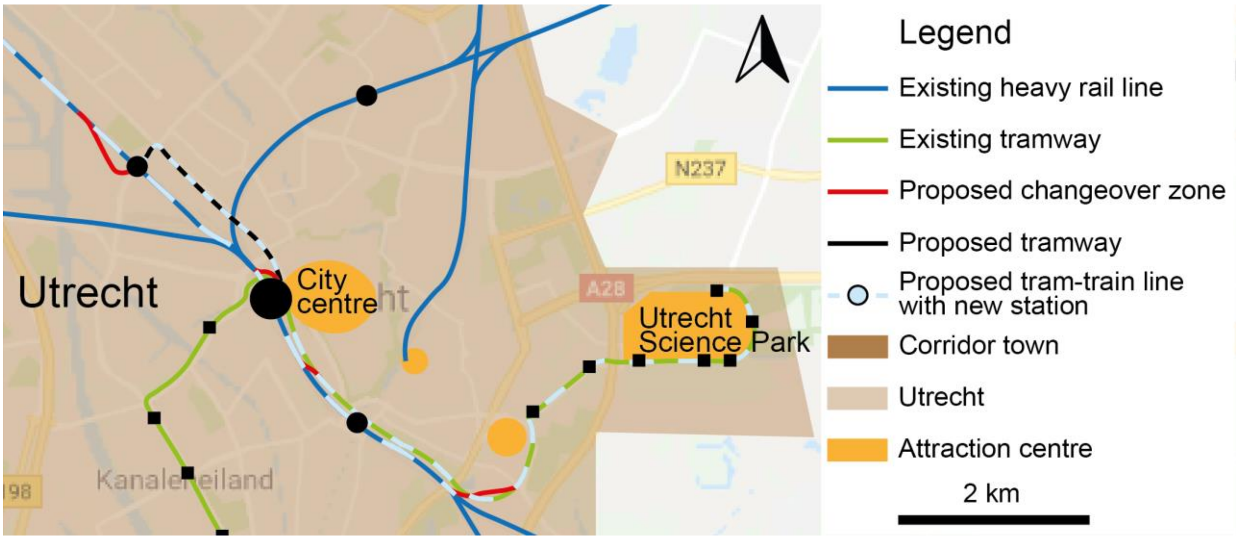


Figure 7-6: Breukelen - Utrecht; connection (red) possibilities. Background: Google Maps.

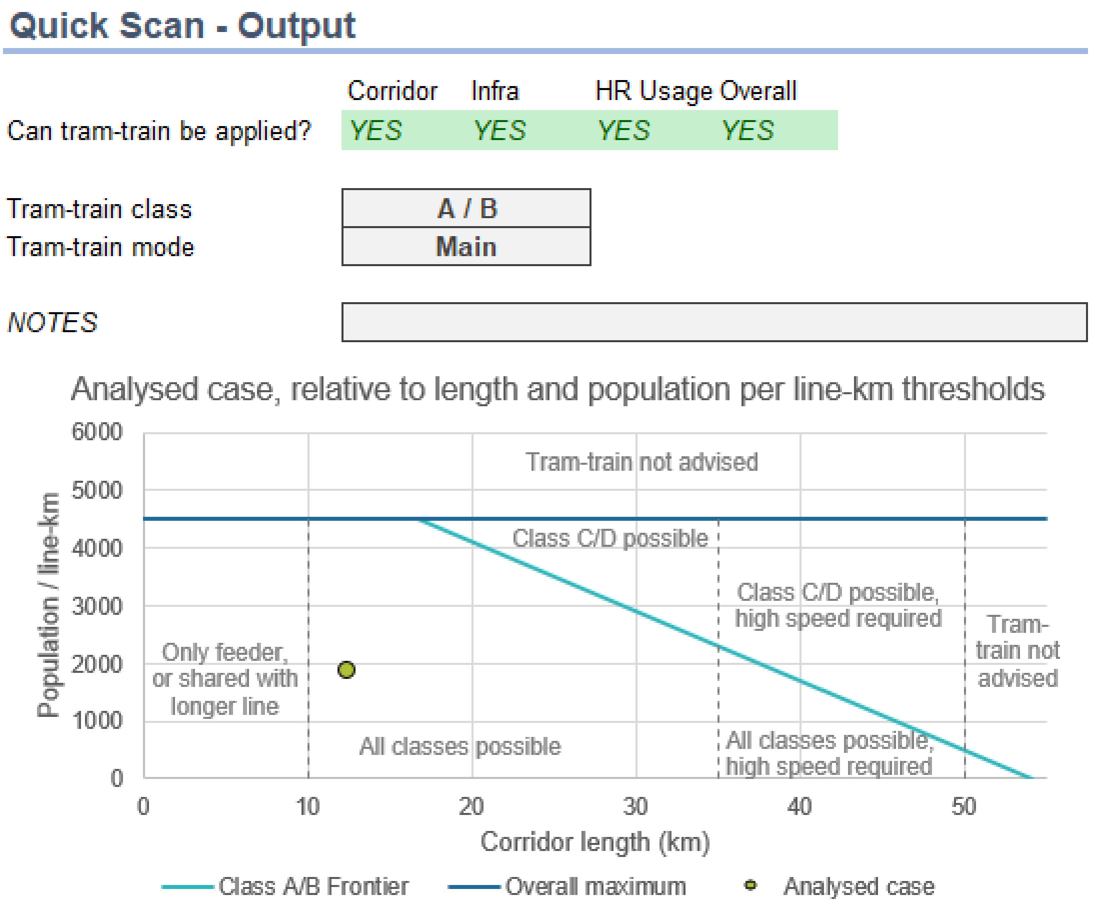
7.2.1 Quick scan

Table 7-2 lists the input for the quick scan for the proposed line between Breukelen and Utrecht.

Table 7-2: Quick scan input for Breukelen - Utrecht.

Input variable	Input value	Notes
Population and corridor		
City population	350 thousand	
Corridor population	23 thousand	Maarssen 13k; Breukelen 10k.
Corridor population spread type	Type B	
Corridor length	12.5 km	Considered from Utrecht main station.
Low-density section population	-	
Low-density section length	-	
Presence of high-quality rail modes along corridor	No	Around Utrecht, a network of high-quality regional trains was developed, but this is focused on transporting people to the main station.
Line envisioned as feeder	No	
Infrastructure		
Heavy rail infrastructure present	Yes	
Tram infrastructure present and usable	Yes	The proposed line will use the Uithoflijn.
Possibility of constructing a new tram line	Yes	
Heavy rail usage		
Number of available train paths	Unknown	
Regional trains	4 tph	2 off-peak. 2 of the 4 could be replaced by tram-train.
Intercity trains	10 tph	
Freight trains	2 tph	
Can tram-train replace regional trains	No	

Input variable	Input value	Notes
Railway layout	Type E	Inverted from the example image, regional trains use the inner tracks.
Length of shared section	12.5 km	Entire heavy rail section will be shared.



Quick Scan - Output

	Corridor	Infra	HR Usage	Overall
Can tram-train be applied?	YES	YES	YES	YES

Tram-train class	A / B
Tram-train mode	Main
NOTES	

Figure 7-7: T-TIST output for Breukelen - Utrecht.

The outcome of the T-TIST quick scan is shown in Figure 7-7. It is immediately visible that tram-train is possible on the investigated corridor. Class A and B can be implemented, although the connection to the Uithoflijn will result in a class A system. The service is advised to be implemented as main mode, which results from the population spread type. The current regional trains can be operated as an express service between Utrecht and Breukelen, which improves the travel time.

7.2.2 Suitability scan

As the quick scan indicates that tram-train is possible for the corridor between Breukelen and Utrecht, the suitability scan was performed. Below, the input for the criteria is described. Table 7-3 shows the corresponding input values for the T-TIST.

1. Maarssen is served fairly well by the tram-train: potentially, more stops can be added. Breukelen is separated from the tracks by the river, so no additional stops can be opened. Due the poor accessibility of the station in Breukelen, the second-to-best category is chosen. If more stops are opened, there are good possibilities for TOD (as with the other stations around Utrecht for the RandstadSpoor).

2. Two potential corridors were analysed; the corridor to Baarn is probably not realistic. However, if tram-train to Breukelen proves successful, the corridor to Baarn could still be checked for suitability. The other lines around Utrecht were not analysed. Conservatively, it is filled out that no other corridors are possible.
3. Maarssen and Breukelen are strongly or very strongly focussed on Utrecht. No detailed origin-destination analysis is carried out on the train network; for Breukelen, a focus on Amsterdam is likely, too. Still, due to the poorer accessibility of Breukelen station, very strong is chosen.
4. A connection to the Uithoflijn results in a direct connection to the University, hospital and provides a connection to the main football stadium. However, the city centre is not directly served by the line. Therefore, it is chosen not to opt for “several other attraction centres”, but “some other attraction centres”.
5. The city centre itself is located very close to the main station (7 minutes’ walk to the Dom church, which is well in the centre) and is reached by a very attractive walk through a shopping mall. However, the university campus is another very important attraction centre. Therefore, the boundary condition is not applicable.
6. There are several options to connect the two networks, but it is unlikely that the connection can be used for other lines. However, it is likely that the connection can only be constructed with over- or underpasses, and space between the tracks is limited at all locations.
7. The Uithoflijn is operated by 2.65m wide vehicles.
8. The Uithoflijn is prepared for double-traction operations.
9. The Uithoflijn has a full ROW B and A alignment. On the university campus, the road is shared with buses. Due to the large number of cyclists on the campus, the section is penalised as having short pedestrian area sections.
10. A frequency of 20 trams per hour is envisioned on the Uithoflijn. The full ROW B/A alignment will improve reliability but bunching at busy stops cannot be prevented.
11. Depending on the location of the connection, Utrecht Centraal will be served on the tram stop or on one of the train platforms. The station is large, and although the tram stop is adjacent to the main building, it is likely that transferring requires more than a 3 minutes’ walk. If the station is served via a train platform, there is some stabling space for an additional vehicle to be added. In Table 7-4, the input values for the second run (service at train platform) are given.
12. It is assumed that tram-trains with a speed of 100 km/h will be used. This is below the line speed (140 km/h). The train section is short and has several stops, so a higher maximum speed will not be very beneficial from a travel time perspective.
13. Cycling is a very common access and egress mode in the Netherlands. Around the main station of Utrecht, over 25,000 cycle racks are available. However, the Science Park is located at a 15 minutes’ ride. Therefore, the bike is not necessarily a competitor to public transport.
14. In the Netherlands, there are several public transport concessions where the regional and rail public transport are required to be coordinated around hubs. For Breukelen and Maarssen, it is expected that there is at least half hourly coordination.
15. Breukelen station is located next to the A2 motorway and offers a large Park & Ride facility, which can be used as a satellite for Utrecht CS. In Maarssen, there is little space for large Park & Ride facilities.

Table 7-3: Overview of the T-TIST suitability scan input for Breukelen - Utrecht.

Criterion	Input	Criterion	Input
1.1 *(Population density)*	C *(medium)*	8.33 *(Extension of platforms)*	A *(none)*
1.2 *(TOD)*	B *(TOD possible)*	8.34 *(Extensive track works)*	A *(none)*

Criterion	Input	Criterion	Input
1.3 *(Very low density)*	- *(not true)*	8.35 *(Vehicle length impossible)*	- *(not true)*
2.4 *(Multiple corridors)*	No	9.36 *(Percentage ROW A/B)*	100%
3.5 *(Focus on city)*	D *(very strongly)*	9.37 *(ROW A sections)*	B *(some)*
3.6 *(2-directional peak demand)*	No	9.38 *(Priority to PT)*	Yes
3.7 *(Dispersed demand)*	No	9.39 *(Pedestrian areas)*	B *(short sections)*
4.8 *(Attraction centre)*	Yes	9.40 *(ROW C)*	A *(none)*
4.9 *(Additional attraction)*	B *(some)*	9.41 *(Gauntlet track)*	A *(none)*
4.10 *(Educational facility)*	Yes	9.42 *(Full ROW C)*	No
4.11 *(Dispersed demand)*	No	10.43 *(Frequency on tram network)*	20 tph
5.12 *(Walking time)*	7’	10.44 *(Frequency >25 tph ROW C)*	No
5.13 *(Height difference)*	A *(none)*	10.45 *(Frequency >30 tph ROW B)*	No
5.14 *(Attractiveness of walking)*	A *(very attractive)*	11.46 *(Serves long-distance station)*	B *(tram platform)*
5.15 *(Poor security)*	No	11.47 *(Stabling space)*	No
5.16 *(Centre adjacent to station)*	- *(not true)*	11.48 *(Transfer; height component)*	A *(no height difference)*
6.17 *(Availability of connections)*	C *(good)*	11.49 *(Transfer; distance component)*	B *(≥3’ walk)*
6.18 *(Connection near station)*	Yes	11.50 *(Transfer; building component)*	A *(same building)*
6.19 *(Effectiveness of connection)*	B *(1 connection/line)*	12.51 *(Vehicle design speed)*	100 km/h
6.20 *(Difficult connection)*	Yes	12.52 *(Equal to line speed)*	No
6.21 *(No connection possible)*	No	12.53 *(Line >35km, v<100km/h)*	- *(not true)*
6.22 *(Gauge difference)*	No	13.54 *(Cycling supports PT)*	C *(very true)*
7.23 *(Tram width possible)*	Yes, 265cm	13.55 *(Public bike-sharing)*	C *(free floating)*
7.24 *(Suitability for 2.65m)*	Yes	13.56 *(Good bike parking)*	C *(most stations)*
7.25 *(Remodelling of corridor)*	A *(no)*	13.57 *(Bike on-board)*	Yes
7.26 *(Undesired track works)*	A *(none)*	13.58 *(Cycling competitor to PT)*	B *(somewhat true)*
7.27 *(Platform gap increased)*	No	14.59 *(Regional PT coordinated)*	C *(≥ twice per hour)*
7.28 *(Vehicle width impossible)*	- *(not true)*	14.60 *(DRT/GRT available)*	Yes
7.29 *(<2.65m on class A/B)*	No	15.61 *(Park & Ride possible)*	Yes
8.30 *(Tram length possible)*	Yes	15.62 *(P&R at stations)*	B *(some stations)*
8.31 *(No track works required)*	Yes	15.63 *(P&R as satellite)*	Yes
8.32 *(Double traction possible)*	Yes		

Table 7-4: Modified T-TIST input for criterion 11, second run (service at train platform).

Criterion	Input	Criterion	Input
11.46 *(Serves long-distance station)*	C *(train platform)*	11.49 *(Transfer; distance component)*	A *(<3’ walk)*
11.47 *(Stabling space)*	Yes	11.50 *(Transfer; building component)*	A *(same building)*
11.48 *(Transfer; height component)*	A *(no height difference)*		

The suitability scan was run twice, to assess the different possible connections (with the tram-train serving the main station at the tram or train platform). Figure 7-8 gives a detailed insight into the scan outcome, for the first run. The graphs indicate that the tram network of Utrecht scores well on suitability for tram-train, as criteria 7 - 10 score (near) maximum points. Furthermore, the access and egress (criteria 13 – 15) scores very well. The penalty scores indicate that the location of the main station and the way the station is served are not optimal. However, the fifth criterion (location of main station) was evaluated between the main station and the city centre, which explains the low score. An evaluation to Utrecht Science Park would yield a in a more beneficial result, as the distance is much longer. When Utrecht CS is served via a tram platform, the ease of transferring to other trains is decreased due to the walking distance. Secondly, at Utrecht CS, there is some stabling space available when train platforms are used. Combined with the higher base score for the second run, an increase for criterion 11 is achieved, from 2 to 7 points. The detailed result for the second run is shown in Figure 7-9.

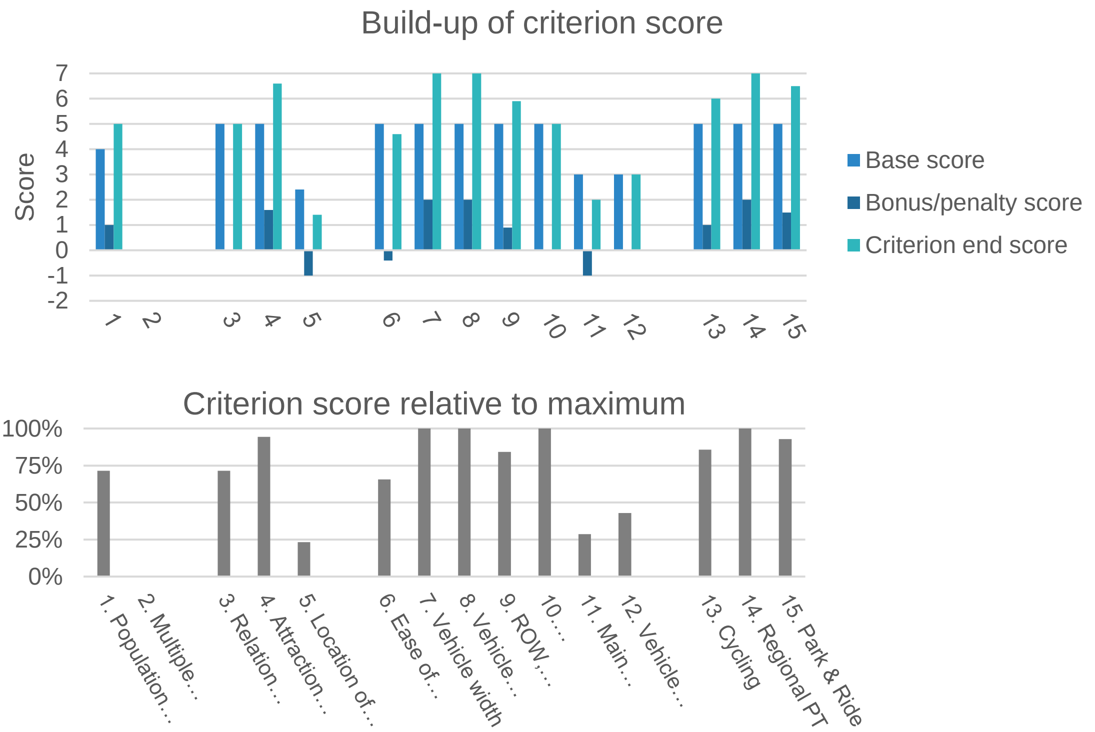


Figure 7-8: T-TIST Suitability scan detail; Breukelen - Utrecht, tram platform.

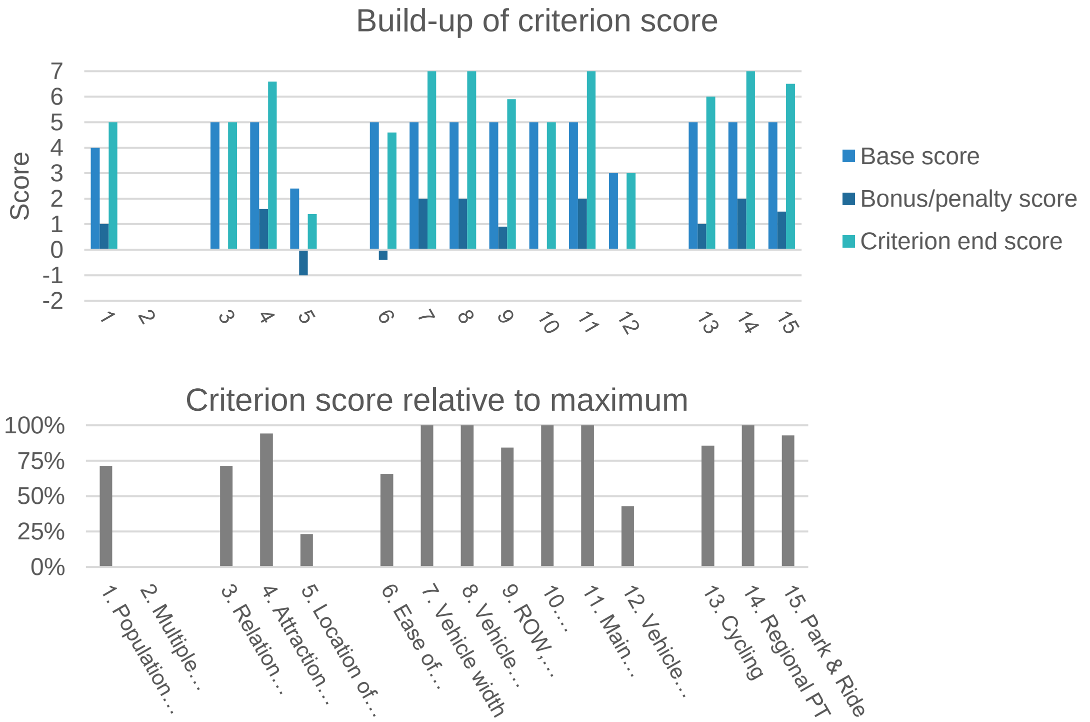


Figure 7-9: T-TIST Suitability scan detail; Breukelen - Utrecht, train platform.

Between the two runs, only the end scores of the sub-set III, to which the modified criterion belongs, were different. The inputs of other criteria than criterion 11, were not changed. The overall score of sub-set III increased from 71% to 82%. The score increase of 5 points also results in an improved total score, from 73% to 76%. Table 7-5 shows the end results for both runs. Also noticeable is the relatively low score for criteria sub-set I, which only includes population density and the possibility of providing multiple corridors. The low score is mainly due to the assumed absence of other possible corridors.

Table 7-5: Breukelen – Utrecht suitability scan results.

Criteria sub-set	Tram platform	Train platform
I. Population & structure	53%	53%
II. Relation region-city	71%	71%
III. PT network	**72%**	**82%**
IV. Access & Egress	94%	94%
Total	**73%**	**76%**

In Figure 7-10, the overall suitability outputs of both runs are combined. In the first run, with an overall suitability of 73%, the T-TIST shows that tram-train is on the border between being suitable and very suitable. After the second run, the score increased to 76%, which is in the very suitable range. For this case study, the T-TIST shows that class A tram-train is possible, and especially when tram-train serves the main station via a train platform, it is also a very suitable solution for the area.

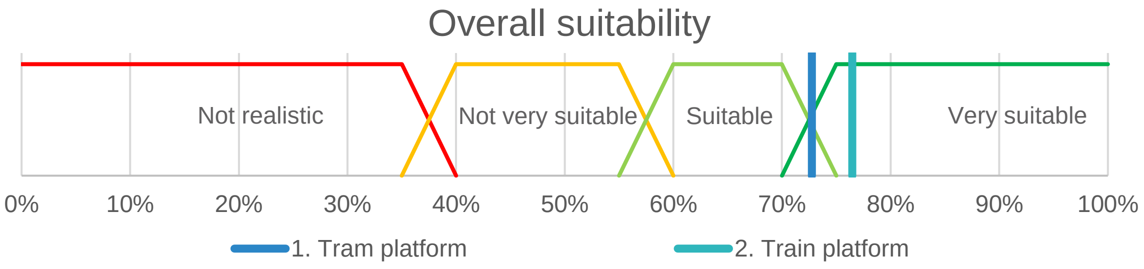


Figure 7-10: T-TIST overall outcome; both runs combined.

With a fast connection to the USP, Breukelen and Maarssen could be ideal commuter towns. A sensitivity analysis of travel time is performed, with the results shown in Figure 7-11. The total score increases to 82%, which is 6% higher than the second run of the base case. The score for criteria sub-sets III and IV have improved a lot and the increase of 6%, relative to a maximum increase of 7.5% for the travel time sensitivity analysis, indicates that the characteristics which influence travel time are suitable for a system aimed at decreasing travel times.

Sensitivity Analysis	Score	
I. Population and structure	20	53%
II. Relation between region and city	59	72%
III. Public transport networks	89	88%
IV. Access and egress	53	107%
Total	**220**	**82%**
Difference	14.4	5%
Relative to max sensitivity increase	71%	

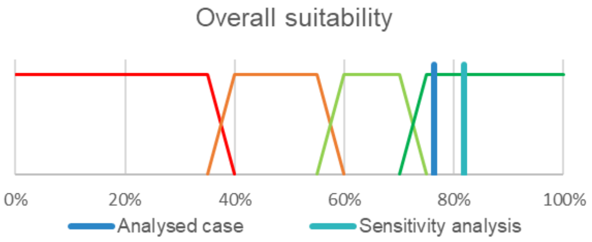


Figure 7-11: T-TIST outcome with sensitivity analysis for travel time.

7.2.3 Technical integration

As class A is the only possible implementation, all interfaces should be checked. The case study is used to evaluate the T-TIST rather than the technical feasibility, which does not require checking all the interfaces. To add some value to the case study, some technical interfaces are briefly reflected upon.

The line between Utrecht and Amsterdam is already equipped with ETCS Level 2, except for the area around Utrecht Central Station. On the main line, braking curve supervision is in place. Moreover, there are no level crossings on the line. As there are shared operations over a significant length, time separation between tram-trains and regular trains is probably not possible. Therefore, tram-train vehicles should be constructed according to the relevant technical specifications. On the ROW A sections of the Uithoflijn, block signalling is used to support drivers about free blocks. This reduces possible interface issues between trams and tram-trains.

The platform interface between low-floor vehicles was solved in the RijnGouweLijn trial (PZH, 2006). However, the vehicles will require retractable steps on the heavy rail network. A dual floor height solution within the vehicles is not advisable, as this limits the number of usable doors and lowers the boarding speed at the tram section. There are a few stops on the tram network where most transport demand originates, so a fast interchange of passengers is required. Therefore, the stations at Breukelen and Maarssen should have low and high platforms. At the existing stations, there is sufficient free space in the alignment to extend the platforms with a low-floor section. If an implementation is chosen where regular trains do not call at Maarssen and Utrecht Zuilen, these stations can be completely rebuilt into low platforms. The tracks are fenced off, so trespassing will probably not be an issue.

For some proposed locations of the connection, it might be difficult to construct a changeover zone which includes sufficient holding space and space for a moving voltage changeover. Therefore, a solution with switchable overhead lines is preferred.

Lastly, as the full heavy rail alignment features quadruple tracks, evacuation procedures of tram-trains on the heavy rail tracks should be considered thoroughly. An evacuation onto the tracks can be very dangerous if the other tracks are not confirmed to be safe.

The technical integration was only touched upon briefly. However, in the short analysis, no unsolvable technical issues were found. It is expected that the technical integration will be possible.

7.2.4 Possible time gains

The current travel time between Breukelen and Utrecht CS is 13 minutes. The travel time between Utrecht CS and USP is expected to be 14 minutes (Donders, 2018). Transferring at Utrecht Central requires at least a 3-minute walk. With a frequency of 20 trams per hour, waiting time is half the headway, thus 1.5 minutes (Vuchic, 2005). The resulting total travel time is 32 minutes. Transferring in the other direction, from tram to train takes longer, due to the lower frequency of the trains. Added to the actual travel times is a transfer penalty of 8 minutes (PBL, 2009), which results in a total experienced travel time between Breukelen and USP of at least 40 minutes, not considering vehicle crowding. The average speed of tram-trains was found to be 37 km/h, which will result in a trip time of 32 minutes. This is equal to the current travel time. When experienced travel time is considered, a reduction of 8 minutes can be achieved (not adjusted for vehicle crowding). Table 7-6 summarises the travel time improvements between Breukelen and USP. Table 7-7 displays the improvements between Maarssen and the USP. Due to the shorter total length, the transfer plays a larger role. The tram-train can provide an absolute travel time reduction of 4 minutes, and a reduction of experienced travel time of almost 12 minutes, which is a reduction of 35 per cent. In Maarssen, some additional improvements on the access side of trips can be achieved when additional stops are opened.

When vehicle crowding is considered, it is assumed that the capacity of a tram-train vehicle is equal to the capacity of a tram on the Uithoflijn. Therefore, crowding does not need to be considered on that part of the section. According to its travel planner, Dutch Railways operates some trains with a capacity of 500 seats on the line between Utrecht and Breukelen, but even in rush hours most trains are shorter (<350 seats). Especially the seating capacity of a tram-train is lower than that of trains. If a solution with tram-trains serving Utrecht CS at a train platform is chosen, an additional vehicle can be added to the tram-train. This increases capacity on the heavy rail section to similar figures as regular trains. Taking this into account, it is not possible to quantify experienced travel time changes due to vehicle crowding, but it can be expected that the vehicles will be utilised at full capacity.

Table 7-6: Effect of tram-train on actual and experienced travel times; Breukelen - USP.

Section	Current time	Av. speed	Tram-train	Av. speed
Breukelen – Utrecht CS (Train)	13 minutes	58 km/h	17 minutes	45 km/h
Utrecht CS – USP (tram)	14 minutes	29 km/h	14 minutes	29 km/h
Transfer	> 5 minutes (actual) > 13 minutes (exp.)	-	0 minutes	-
Total time	**> 32 minutes (actual)** **> 40 minutes (exp.)**	**< 36 km/h (actual)** **< 29 km/h (exp.)**	**32 minutes (actual)** **32 minutes (exp.)**	**37 km/h***

* The overall average speed of tram-train is an estimation based on the state-of-the-art analysis.

Table 7-7: Effect of tram-train on actual and experienced travel times; Maarssen - USP.

Section	Current time	Av. speed	Tram-train	Av. speed
Maarssen – Utrecht CS (Train)	8 minutes	56 km/h	9 minutes	50 km/h
Utrecht CS – USP (tram)	14 minutes	29 km/h	14 minutes	29 km/h
Transfer	> 5 minutes (actual) > 13 minutes (exp.)	-	0 minutes	-
Total time	**> 27 minutes (actual)** **> 35 minutes (exp.)**	**< 31 km/h (actual)** **< 24 km/h (exp.)**	**23 minutes (actual)** **23 minutes (exp.)**	**37 km/h***

* The overall average speed of tram-train is an estimation based on the state-of-the-art analysis.

The tram-train might be offered at a higher frequency than the current regional services are provided, as there is probably some spare capacity on the used tracks and the services are not constrained by capacity issues further away from Utrecht.

Lastly, passengers of regional trains between Utrecht and Breukelen (and beyond) might benefit from the introduction of the tram-train as well. The regional trains can skip Utrecht Zuilen and Maarssen, which increases the average speed and reduces the travel time.

7.2.5 Breukelen – Utrecht: conclusion

Overall, tram-train is a very suitable solution for the line between Utrecht and Breukelen. Considering the location of the city centre, tram-train would not necessarily be a good solution, but the Utrecht Science Park can be regarded as another main attraction centre. The travel time towards the USP will improve, especially when the transfer penalty in experienced travel time is considered. On the other hand, the travel time towards the main station will increase slightly.

Passengers from Breukelen still have the option of using regional trains, which could even be sped up as the stops in Maarssen and Utrecht Zuilen can be skipped.

7.3 Validation of the T-TIST

In the verification of the separate models (section 5.3), some shortcomings of the quick scan and suitability scan models were identified. As the T-TIST is based on these models, it was expected that these shortcomings were also encountered while performing the case studies. However, the implementation of the models in the T-TIST can be adjusted to overcome some of the deficiencies. In this section, the T-TIST is validated on the requirements of usability and reliability of the results, based on the two performed case studies. As data collection is an important part of an analysis with the aid of the T-TIST, the ease with which data can be collected is also assessed as part of the validation.

7.3.1 Quick scan

The quick scan was performed for both case studies.

Data collection

The acquisition of population and corridor data took little time, as the required inputs are easily obtainable via public sources. The presence of infrastructure is generally known, although the usability of the tram network (such as the width of the vehicles) might need to be researched first. The possibility of building new tramways will be known by the users of the tool, as this should be decided when searching for public transport solutions.

The data on heavy rail usage can be more difficult to obtain. Especially the number of available train paths will likely result from detailed capacity studies, but there might be situations in which an accurate estimation can be made. Current heavy rail services can be determined by data from the IM. Timetables provide an initial estimation of the number of passenger services.

Evaluation based on case study Baarn - Utrecht

The initial result of the quick scan showed that the population was too large for tram-train, but graphical representation indicated that the value was not much higher than the threshold. Therefore, a critical assessment of the population figures revealed that the initial value could be a too large estimation. This issue is a result of the pragmatic approach of using total town populations, rather than catchment areas or OD-matrices. On the other hand, the relations in the model are rough estimates as well, so very accurate inputs do not necessarily improve the output accuracy.

The heavy rail layout on the corridor features a triple-track section, which was not considered in the model. Therefore, a description of how to deal with triple-track sections is added to the T-TIST Manual. Moreover, the issue of compound sections is noticed in the T-TIST as well. The section through Soest has single track, but is not assessed by the tool, as the tool focuses on the shared section. Therefore, the T-TIST can be improved to include multiple heavy rail sections, which should be assessed individually. This can even result in the tool suggesting various classes for different sections. For instance, the section through Soest could be transformed into a class C section. The division into separate sections with different outputs could also ease the technical integration in a final step.

In this specific case, the T-TIST indication of probable limited frequency on the shared section and the user assessment of the section through Soest resulted in the decision not to perform the suitability scan. Both the usability and reliability of the T-TIST would be improved if it was able to assess the separate sections.

Evaluation based on case study Breukelen – Utrecht

The output of the quick scan indicated that class A and B implementation are possible. This results from the availability of an existing tram line and the possibility of constructing new lines. However, in the case when the existing tram network is usable, it will be unlikely that one choses for a class B implementation (in Nantes, the tram network was not usable).

7.3.2 Suitability scan

The suitability scan was only performed for the second case study, the line between Breukelen and Utrecht Science Park.

Data collection

The data required for the suitability scan is mostly qualitative. It was noted that this could result in inconsistencies between various users of the tool; which was a reason to provide a manual which supports in deciding on correct inputs. The case study gave insight in some additional issues which were not found during the verification of the models.

The qualitative data can easily be obtained through (virtual) site surveys. Having local situational knowledge can speed up the data collection process and can improve the quality of the data.

Evaluation based on case study Breukelen – Utrecht

When performing the suitability scan, it was found that it is required to have an indication of possible routes and locations to connect the tram and train networks. If there are no ideas on possible routes and locations, it is not possible to fill out criteria of category III (PT Network). On the other hand, the suitability scan is also able to assess various alternatives within the tram-train context. The T-TIST could clearly indicate the effect of the different connections, by re-analysing the service level of the main station.

In Breukelen, it is unlikely that the station serves the full population, as it located relatively out-of-town. The suitability scan partly resolves this deficiency of the quick scan, by assessing the population density and relation to the main city. The suitability scan indicated that the proposed line does not score very well on the location of the main station. As was noted with the given inputs, Utrecht has two main attraction centres: the city centre very close to the station, and the USP, which is at the edge of the city. In the analysis, the walking distance to the city centre is regarded. The T-TIST shows the relatively poor score on criterion 5, but also indicates that several other criteria score very well.

The result of the sensitivity analysis was supported by the outcome of the travel time analysis. The T-TIST indicated that the proposed corridor would be able to provide travel time improvements. The analysis of actual and estimated travel times revealed that the tram-train would be able to provide significant improvements to travel times, which concludes that the sensitivity analysis is reliable for this situation.

7.3.3 Recommended future T-TIST upgrades

Based on the case studies, some additional nice-to-have features were come up with. These features do not influence the implementation of the models or the accuracy of the results in the T-TIST but add additional value to the tool’s output. First of all, it would benefit the usability of the tool if the information provided in the manual could be included in the tool.

In the Breukelen – Utrecht case study, two alternative routes were analysed. The results of the tool were compared manually, which indicated the difference. However, the usability of the tool could be improved when the results of various runs can be stored in the graphs, such that the results of different alternatives are visible without post-processing.

Similarly, a travel time analysis was performed manually. Although a qualitative sensitivity analysis on travel time is included in the suitability scan, a complete travel time analysis could be included in the T-TIST and explicitly indicate the advantage of tram-train to travellers.

7.4 Conclusion

In the chapter, the designed T-TIST was tested with two case studies, to evaluate its performance in terms of usability and reliability of the results. As a first case, a corridor between Utrecht and Baarn was analysed. The quick scan of the T-TIST showed that tram-train is probably not possible for that corridor, as the population is too large. After critical evaluation of the input, the corridor could be suitable, but the infrastructure was not optimal either. Therefore, no further analysis of the corridor was performed. Secondly, a line from Breukelen, via the Utrecht main station towards the Utrecht Science Park was analysed. The quick scan indicated that implementation of tram-train would be possible. After performing the suitability scan, it was found that tram-train is very suitable for the corridor, especially when the tram-train can be served on the train platforms of the main station.

The case studies showed that the T-TIST provides comprehensible results within a reasonable amount of time, while requiring easily obtainable inputs. The results of the quick scan are clear. It was found that the issue of the model being unable to deal with compound lines can be solved in the tool, by enabling a user to define various sections. For each section, the tool should indicate the possibilities. However, the final conclusion based on the combination of the sections might be very location-specific. The suitability scan outcome is presented in such a way that it is directly visible what the overall outcome is, but also how the various criteria score. This information can be used to see why tram-train is (un)suitable. Users can adjust certain inputs and directly see the result of the modifications.

Overall, the T-TIST meets the set requirements: the tool is usable, and the results are reliable. It should be remembered that the tool provides an indication, and that the final output should be interpreted carefully and relative to the local conditions. A critical assessment of the results is always required.

Finally, some possible future additions to the T-TIST were discussed: the possibility of directly comparing differences between alternatives and including a travel time analysis in the tool.

8 Conclusion

The objective of this thesis was to develop an evaluation model to determine whether tram-train can be applied in an urban region and whether it is a suitable solution to achieve desired improvements to the public transport system. The research questions which were formulated in section 1.2.2 served as guidelines according to which the model was designed. In this chapter, brief answers to the sub-questions, as well as the main question are given.

8.1 Public transport demand: objectives for improvement

- **What are objectives for improvements in (sub)urban public transport? And what measures could be taken to achieve these objectives?**

In this thesis public transport was regarded from the perspective of three main stakeholders; the passengers, the operators and the government. Considering their perspectives, five objectives for improvements in urban public transport have been defined:

- Improving line capacity: According to White (2009), line capacity depends on the frequency and train capacity. For buses and trams, the possible frequency has no hard constraints. In practice, it should not exceed 20 vehicles per hour to prevent bunching. On heavy railways, frequency is constrained by block safety systems and the homogeneity of the traffic. Train capacity depends on the length and width of vehicles. For trams, the width can be constrained by narrow streets for example, while platform length is generally decisive for the length.
- Shortening travel times: Trips are made up of several components but shortening one component can result in extending another. Travel time can be decreased by increasing the frequency and improving the average speed. The latter can be achieved through various methods, such as reducing the number of stops, reducing dwell times or improving acceleration and deceleration characteristics of vehicles. For passengers, also the experienced travel time is important. Especially in urban transit, transfers were found to add considerably to the experienced travel time. Elimination of a transfer was found to reduce the experienced travel time by at least 8 minutes.
- Increasing network coverage: Network coverage is about the accessibility to a public transport network. It was found that for high-quality public transport modes, the catchment area of stops increases. Moreover, when cycling is stimulated as an access mode, the catchment area of stops can be increased to over 2 km. Moreover, coordinated access and egress public transport improves overall coverage of a system.
- Improving sustainability: Electrical vehicles emit no exhaust fumes, but tyres of buses still produce particulate matter. Rail-bound vehicles do not have this disadvantage. Moreover, rail-bound vehicles are more energy efficient due to the reduced friction.
- Improving attractiveness: Rail-bound vehicles benefit from the ‘railbonus’, which indicates that passengers prefer trams over buses in ceteris paribus conditions. Moreover, trams produce less noise on straight sections, compared to diesel buses.

8.2 Public transport supply: tram-train and ‘traditional’ modes

- **How can a tram-train system be defined in this research?**

Tram-train was developed in the German city of Karlsruhe. A line was created which was operated as a tram within the city centre and as a train on the regional heavy rail line. The heavy rail tracks were shared with ‘real’ trains. This concept was extended, and other forms of tram-train were developed; both with and without track sharing on the heavy rail and tram section. This distinction results in four classes:

- Class A: Shared operation on the heavy rail and tram network.
- Class B: Shared operation on the heavy rail network, not on the tram network.
- Class C: Shared operation on the tram network, not on the heavy rail network.
- Class D: No shared operation at all.

Secondly, tram-train can be positioned along a corridor in three ways, partly depending on the implemented class:

- Main mode; where trains only serve the terminus or are replaced entirely by the tram-train. All classes can be implemented as main mode.
- Secondary mode; where regional trains serve several (larger) stations along the tram-train route. As regional trains are retained, only class A and B can be used as secondary mode.
- Feeder service; where tram-train serves as a lower-level access mode to a higher-level (rail) mode, such as a metro or urban rail network (S-Bahn / RER). This mode can be used on class C and D lines.

- **What are the operational characteristics of tram-train systems, in terms of capacity, stop spacing, speed, etc? And how does tram-train compare to ‘traditional’ modes?**

Several existing tram-train lines were analysed on their operational parameters and compared to urban tram, and regional tram and train. The analysis was performed for the separate tram- and train sections, as well as for the full lines. Table 8-1 displays the results. As expected, there are no significant differences between urban tram lines and the tram sections of tram-train lines. On train sections, it was expected that the stop spacing of tram-train lines would be smaller than of regional trains. The operational characteristics of tram-train systems are on the lower boundaries of regional train systems, which results from the lower average speed. Tram-train vehicles are in between regional trams and trains in terms of technical vehicle parameters, which is visible in Table 8-2.

Table 8-1: Comparison of operational parameters.

Parameter	Regional train	Tram-train; train section	Urban tram	Tram-train; tram section	Regional tram	Tram-train; full line
Mean line length	> 20 km	23.6 km	5 – 20 km	6.7 km	10 – 40 km	32.6 km
Mean number of stops	--	11	--	13	--	25
Mean stop spacing	2 – 5 km	2.4 km	200 – 600 m	450 m	0.4 – 2 km	1.7 km
Mean speed	> 60 km/h	45 km/h	15 km/h	19 km/h	30 - 45 km/h	37 km/h
Mean trip time	--	32 minutes	--	20 minutes	--	55 minutes

Table 8-2: Comparison of vehicle parameters.

Parameter	Regional train	Tram-train; train section	Urban tram	Tram-train; tram section	Regional tram	Tram-train; full line
Max. speed	> 100 km/h	100 km/h	< 70 km/h	< 70 km/h	< 80 km/h	100 km/h
Vehicle width	< 315 cm	265 cm	220 – 265 cm	265 cm	< 265 cm	265 cm
Vehicle length	50 – 200 m	> 35 m	< 35 m	< 75 m	< 75 m	> 35 m

Parameter	Regional train	Tram-train; train section	Urban tram	Tram-train; tram section	Regional tram	Tram-train; full line
Acceleration	0.6 – 1.0 m/s^2	< 1.3 m/s^2	< 1.3 m/s^2	< 1.3 m/s^2	< 1.3 m/s^2	< 1.3 m/s^2
(Emergency) deceleration	0.8 – 1.2 m/s^2	(> 2.5 m/s^2); 1.2 m/s^2	(> 2.5 m/s^2); 1.2 m/s^2	(> 2.5 m/s^2); 1.2 m/s^2	(> 2.5 m/s^2); 1.2 m/s^2	(> 2.5 m/s^2); 1.2 m/s^2

8.3 Applicability of tram-train

- **What are the (operational) advantages of integrating tram and train systems? And what are the possible disadvantages?**

Several reference systems have shown large increases in passenger numbers after introduction of the tram-train concept, which indicates that tram-train can be beneficial to the passengers. The success of tram-train follows from several advantages of tram-train over separated modes. However, it is evenly important to be aware of the disadvantages of tram-train. Table 8-3 provides an overview of the main advantages and disadvantages of tram-train.

Table 8-3: Advantages and disadvantages of tram-train.

Advantages	Disadvantages
Elimination of transfers and faster trips to city centres. *This provides significant benefits to passengers in terms of experienced travel time. Moreover, tram-trains can bypass orbital railway lines, by providing direct access into the city.*	**Expensive rolling stock.** *Tram-train rolling stock is more expensive than regular trains or trams, because of the specific requirements.*
Larger catchment area in regional towns. *Tram-train vehicles have better acceleration and deceleration characteristics than regular trains. This allows them to serve more stations in the same time.*	**Institutional complexity.** *A tram-train system requires cooperation of many stakeholders. These include local and regional operators, as well as national train companies and infrastructure managers.*
Limited new infrastructure required. *Existing infrastructural networks are used, so only a connecting chord needs to be constructed. Examples, such as Kassel, do show that these chords might require complicated civil works.* *On the other hand, a tram extension of a train line can result in easier integration in cities.*	**Technical and operational complexity.** *Tram- and train systems are two distinct systems, with different technical specifications and operational principles. Integration of the two systems results in several issues at interfaces between the system components.*
Improved service on long distance lines. *As tram-train serves the region surrounding a city, regional trains can be operated as express service along a part of the line. This decreases travel time between the city and towns further away.*	**Political issues.** *As tram-train lines serve a larger region, there can be several political bodies involved, with different demands. Van der Bijl (2018) notes that a single transit authority is desirable, as this eases the decision-making process.*
Sustainability and ‘railbonus’. *Tram-train is a sustainable mode, and attractive to passengers.*	**Limited capacity.** *Tram-train vehicles are smaller than regional trains, and due to their lower maximum speed utilise more capacity on long railway sections. The offered transport capacity on regional corridors might be insufficient.*

- **What (socio-economic and urban planning) characteristics of an urban region make the region suitable for a tram-train system?**

The applicability of tram-train for an urban region depends on many criteria. The criteria that were found to be relevant within the scope of this thesis can be distributed into four categories:

I. *Population of city and regional corridor.*
Tram-train was found to be most suitable in cities with a population between 100 and 400 thousand inhabitants, although no clear upper boundary could be defined. The absolute population of a regional corridor is not directly related to the applicability of tram-train but should be regarded relative to the corridor length. For the population per line-km, upper and lower boundaries were determined. Moreover, for the applicability of class A and B

systems, a linear frontier has been estimated. The actual density around stops further influences the suitability of tram-train. Moreover, due to the relatively low average speed of tram-train, the corridor should not be longer than 35 km.

II. *The relation between the urban region and the main city*.
Tram-train can be successful if there is a strong social and economic focus from the region towards the main city, and when attraction centres are not located adjacent to main railway stations. Direct services towards large educational institutions provide additional transport demand.

III. *The existing rail networks.*
A tram-train system should not become a direct competitor to existing high-quality rail modes into the city centre. There should be heavy rail infrastructure present, but tram infrastructure is not required. However, implementation will be cheaper when only a short connection needs to be built. The possibility of integration with the existing tram network depends on the vehicle dimensions and the level of service. If the desired tram-train vehicles are wider and longer than the existing tram fleet, this might require extensive modifications of the tram network. Secondly, especially class A and B tram trains require a high punctuality because of their integration within a heavy rail timetable. Long sections of ROW C, pedestrian area and gauntlet track, and short headways make a tram network less suitable for tram-train lines. The possibility of integration with the heavy rail network mainly depends on the track layout and the capacity consumption. The design speed of the tram-train vehicles, which is generally 100 km/h, influences the required capacity. However, a new standardised vehicle with a top speed of 120 km/h is currently under development.

IV. *Access and egress modes.*
Cycling can be a valuable addition to a public transport network. When good facilities are offered, cycling increases the catchment area of stations. Tram-train can be supported by bicycles in cities where the bike is not a direct competitor. Moreover, tram-train can be more successful if coordinated with regional public transport in small hubs and when park & ride can be offered in the scheme.

Of these criteria, the serviceable population per line-km was found to be a very important criterion considering the applicability of tram-train, although the capacity on heavy rail tracks can limit the possible frequency and thereby the offered capacity. The criteria on the relation between the urban region and main city (category II) are the most important when defining the suitability of tram-train. Those criteria are specifically related to the basic concept of tram-train and define the transport demand for such services.

8.4 Technical and operational integration

- **Which challenges arise when urban rolling stock is to be used on heavy rail, and vice versa? How can these be solved?**
- **Which challenges arise when heavy rail and tramway infrastructure are connected? How can these be solved?**
- **What are the differences in operational aspects between tram and heavy rail systems? How are these solved in tram-train operations?**

A framework was designed to systematically identify the interfaces between components (rolling stock, infrastructure and operational aspects) of tram and train systems. With this framework, potential issues that could arise when tram and train are integrated were found. These issues are captured in a library (appendix F), which can be used as a reference document when performing feasibility studies on tram-train. Several issues are listed as attention points, while for other issues possible solutions were provided. For these solutions, the library displays qualitative assessments on impact on cost, operations, rolling stock and infrastructure. No generally unsolvable technical and operational issues were found, but a tram-train system should be optimised to locally existing conditions. There can be specific local conditions which result in an interface issue being unsolvable, thereby making tram-train technically unfeasible.

8.5 Development of the model and T-TIST

- **How can the acquired knowledge of tram-train be captured in an evaluation method?**

A three-step top-down approach was used to determine the applicability and suitability of tram-train. In the first two steps, the urban region is assessed on the four categories of criteria, while the last step focuses on the technical feasibility.

In the first step, the quick scan, it is analysed whether tram-train is applicable. Based on quantitative data on population, corridor length, infrastructure and heavy rail usage, the possibility of implementing each tram-train class and mode is determined. Verification of the developed model indicated that accurate results are obtained for regions with a main city and less populated surrounding. Due to insufficient available data, it was not possible to define relations for heavily urbanised regions. Secondly, the developed model could not be applied directly to compound lines, where only parts of the line are shared with other trains.

In the second step, it is analysed whether tram-train is a suitable solution for an urban region. A qualitative analysis of 15 criteria and an assessment of potential transport capacity is performed to determine the suitability of tram-train. For criteria with certain thresholds, boundary conditions were implemented in the model. A sensitivity analysis is performed to discover how well a proposed tram-train line can fulfil a desired improvement objective. The designed suitability scan could be verified for urban regions, where the main city features a tram network. If the tram network is in another part of the line, the required inputs for the suitability scan cannot be determined.

For some tram-train classes, several interfaces between the tram and train systems might not occur, as certain system components are absent. Based on the quick scan output, the relevant interfaces in the library can be indicated.

- **How can the developed model be transformed into a usable tool?**

The Tram-Train Implementation Support Tool (T-TIST) was designed according to the following specifications:

- The T-TIST should include the developed models and indicate relevant interfaces of the technical solution library.
- The T-TIST should be easy to use by the targeted audience.
- The T-TIST should provide comprehensible results.
- The T-TIST should be easily adaptable.

The T-TIST was created in Microsoft Excel and requires easily obtainable inputs. In two steps, the tool performs the quick scan and suitability scan models. For each step, a single output window indicates the main results: the possible classes and mode for the quick scan, and the suitability score for the suitability scan. Additional supportive results are provided, to place the main results in context. In the T-TIST, an interactive environment is created where users can see direct results of altered inputs. A manual is provided with the tool, to support users in choosing correct input categories.

Overall, the T-TIST meets the set requirements: the tool is usable in an early exploratory project phase, and quickly provides comprehensible results. It should be remembered that the tool provides an indication, and that the final output should be interpreted carefully, considering the local conditions. A critical assessment of the results is always required.

8.6 Main research question

The sub-questions provide supportive results, which are used to answer the main question which was posed in section 1.2 of this thesis.

- **How can applicability of tram-train in an urban region be evaluated using a generalised approach, based on both public transport and city characteristics?**

Tram-train has been applied successfully in various cities throughout Europe. An analysis of reference systems showed that tram-train is a flexible mode and can be adapted to many local conditions. Although all analysed tram-train systems can be categorised into four classes, there is no generalised concept of tram-train that is used in each city. In this thesis, a model was developed that works well for urban regions where it is studied to implement a specific concept of tram-train: aiming to connect a tram network in a city to a regional heavy rail network which serves smaller regional settlements. Within this setting, the model can distinguish between cities with and without an existing tram network.

In this thesis, the effectiveness of a tram-train system was evaluated on improvement objectives. Overall, tram-train can reduce (experienced) travel times between regional settlements and a city centre, mainly by eliminating transfers. Moreover, tram-train can increase the coverage of the public transport network. Tram-train performs better than buses in terms of sustainability and attractiveness but does not provide additional benefits compared to other rail-bound modes. The ability of a tram-train line to improve the transport capacity is strongly dependent on local conditions.

Several applicable characteristics of the city, regional corridor and existing rail networks were identified. For the overall possibility of tram-train being successfully implemented, the number of inhabitants per line-km along the corridor and available capacity on the heavy rail tracks were found to be very important criteria. These criteria relate to the potential transport demand and transport capacity. The length of the regional corridor was found to be relevant as well, relating to travel time.

The presence of a tram network is not required for a successful tram-train network and absence might even be beneficial from a technical point of view. When specifically building a tram line for tram-train, issues with interfaces between the tram and train network can be avoided. However, it should be acceptable socially and politically to construct a new tram line.

The suitability of a tram-train line is determined by assessing 15 criteria, which are distributed over four categories. Category I and IV, population and structure, and access & egress, are generally corridor-specific criteria. Category II, relation between city and region, is mostly fixed for the entire region; a very poor score on this criterion indicates that tram-train might not be suitable. Lastly, category III, the existing rail network, is related to the route through the city. The designed framework can be used effectively to assess variants of a tram-train line and to compare them to existing systems.

9 Discussion and recommendations

In this chapter, the applicability of the model and tool are discussed, as well as the used methodology. Based on the discussion, recommendations for future research, applicability of tram-train, and improvements of the T-TIST are provided.

9.1 Overall applicability

It was aimed to develop a generalised model for the applicability of tram-train. However, the concept of tram-train proved to be very flexible, and difficult to generalise. As the reference systems are mostly class A lines, based on the Karlsruhe model, the overall applicability of the model is reduced to cities and regions which resemble the Karlsruhe model. These feature a main city with a tram network, and a region where tram-train is offered as a train. There are situations (such as the Cádiz system) in which the developed model cannot be used, but in which tram-train can still be very suitable. Similarly, the model proved not to be applicable for all types of designed networks. Following class A systems, a connection between the train and tram networks is expected. The “French” approach (Kühn, 2018), such as implemented in Nantes, is not captured well by the model. In this approach, tram-train was chosen for the easier technical implementation of tramways compared to heavy railways, rather than to connect a region to the city centre.

It was noted that the institutional context around light rail projects plays a very important role (Van der Bijl & Kühn, 2004; Naegeli et al., 2012; van Oort et al., 2014). However, it was decided to leave the institutional situation out of scope for this thesis. Even if the T-TIST indicates that tram-train could be a very suitable solution, which would lead to huge improvements for travellers, there is still a risk that the involved stakeholders cannot come to an agreement.

Secondly, cost was left out of the initial research scope and is only considered to a small extent (as sensitivity for the suitability scan and in the technical solution database). However, cost plays an important role in the decision-making process of large infrastructural projects. It was pointed out that tram-train vehicles are more expensive than regular trams. The technical solution database can be extended to quantify the cost of solutions. In the current form, it provides a set-up to further cost estimates.

As several reference cases had to be analysed on many points, a pragmatic approach to the data collection has been used. However, this reduces the accuracy of the acquired data. As the tool is used to provide a quick indication, the less accurate data can be used. If a more detailed feasibility study is performed, one should ensure that this is based on higher-quality data.

9.2 Quick scan

The quick scan is based on a very pragmatic indicator of servable population. The full population of towns along the line is used, rather than a more detailed catchment area around stops. This is an easily obtainable figure and is of acceptable quality for the quick scan. However, there are cases in which this figure cannot be used as a realistic indicator for the potential population, such as indicated by the case study of Breukelen, where the station is on the other side of a river. Similarly, long, narrow towns which have developed perpendicular to a railway will likely not completely fall into the catchment area. The suitability scan compensates for this by criteria on population density and access, but this effect is relatively limited.

The maximum servable population per line kilometre is set as a constant value, independent of line length. However, this is a reason why the quick scan performs poorly for heavily urbanised areas (Cádiz, Sheffield), where lines are shorter and populations larger. The fixed value is a result of the reference cases used. For the class A/B frontier, a similar reasoning holds. Based on the reference systems, a linear frontier was estimated. It may well be possible that the frontier is decreasing exponentially, which would increase possible populations for short lines. However, too little data was available to reliably estimate an exponential function.

9.3 Suitability scan

The suitability scan is an extension to works of Van der Bijl & Kühn (2004) and Naegeli et al. (2012), who both created a checklist on tram-train. In this thesis, their checklists were adapted in such a way they could be used for a qualitative analysis. The criteria were assessed on present-day relevance and the checklists were extended by new present-day knowledge.

The reference checklists include more criteria than considered within the scope of this research. The value of the suitability scan can be improved when criteria on these other categories, such as institutional complexity, are included. Moreover, the existing criteria can be extended with additional questions. However, given the position of the tool early in an overall project process, the time required to perform an analysis with the tool should not become too extensive.

9.3.1 Methodology

In the suitability scan, a weighted-sum multi-criteria analysis is used to score alternatives and generate a suitability score. Generally, the method is used to compare between various alternatives (Triantaphyllou, 2000). In this thesis, there might not be a direct alternative, which is why reference cases were used to define suitability ranges. The ranges were defined using some fuzzy logic, which is not an undisputed method for governmental purposes (Dodgson et al., 2009). However, the suitability scan does not aim to indicate a best alternative, but to indicate the probability that tram-train can be implemented successfully. For this purpose, the authors find the fuzzy logic a suitable method.

To be able to compare criteria with different data types, all data was categorised, and normalised scores were given. However, in the normalisation process, there is some risk of bias. For some criteria, certain inputs have a relatively similar influence on the result, so their scores should not differ too much. The use of normalised scores for yes/no questions (0 or 5 points) implicates that the effect of such binary questions can be larger than for Likert-scale questions, where intermediate values are possible as well. The accuracy of the suitability scan can be improved by fine-tuning the way the criteria are posed, so that most input follows from the same data types and less score normalisation is required. The weights for the criteria were determined in consultation with five experts from the field. It was ensured that they awarded a similar number of points in total, so their scores could be compared.

The sensitivity analysis is based on a method where scores and weights are modified. Except for the cost sensitivity where scores are reduced to 0 points, the result of the modifications will be an increased end score (as a result from the weighted sum method). A downside of this method, as the modified score is compared to the initial maximum score, is that a suitability score of over 100 per cent is possible. However, if the maximum score is increased by the maximum possible sensitivity score as well, there will only be a minimal effect on the outcome. Secondly, the sensitivity is also determined based on the difference between the initial score and the modified score, relative to the maximum possible score improvement, which is a more specific indicator for a certain improvement objective. In the tool design, it was ensured that the results of the sensitivity scan were provided in a clear manner.

9.4 Technical integration

Several reference cases were studied in literature and through site visits, which resulted in an extensive list of interface issues and solutions. However, the list might not be complete. In future projects, new issues might arise to which solutions need to be developed. The rough assessment of the solutions is performed very pragmatically and generalised. The actual implementation of solutions is always dependent on local conditions, which could result in different impacts on the analysed criteria.

9.5 Recommendations

In this section, recommendations for future research into the topic of tram-train are provided. Moreover, a general note about the applicability of tram-train is made, aimed at decision-makers. Lastly, some proposed improvements to the T-TIST are discussed.

9.5.1 Further research

The designed model is mostly based on reference systems which are according to the Karlsruhe model. Therefore, an analysis of systems which were designed according to a different concept (such as Lyon), and more transformed lines (such as Alicante and Arhus) could extend the applicability of the model. The applicability of the model on other modes of transport can also be studied. The designed framework in which first the overall applicability of a mode is determined, after which a more in-depth suitability analysis is performed might also be useful in other fields.

In this research, the operational parameters of tram-train were quantified. The institutional and political context were not included in the scope of this thesis, and cost was regarded very superficially. Further quantitative research into these aspects of tram-train will extend the knowledge and understanding of the applicability of tram-train from a wider scope.

9.5.2 Applicability of tram-train

It was found that several possible implementations of tram-train exist. Tram-train can be applied very flexibly and is adaptable to many local conditions. Class C systems, where tram-train replaces the existing heavy rail operations are the easiest to implement, from a technical and institutional point-of-view. On the other hand, class A and B systems have the potential to enlarge the system scope of urban public transport networks, given there is sufficient available capacity on the heavy rail tracks. For medium-sized cities with relatively small commuter towns, tram-train lines serving main attraction centres away from stations can significantly improve the attractiveness of public transport. However, if urban development is concentrated around large train stations and few attraction centres are located elsewhere in the city, tram-train will have limited added value.

Overall, it is advisable to standardise implementation of class A and B systems as much as possible between different urban regions in a country. This eases the technical integration and enables the use of standardised vehicles, such as proposed by Streeter (2018). Additional benefits of standardised implementation are that economies of scale can be obtained.

9.5.3 Improvement of the T-TIST

The main proposed improvement to the tool would be to create a stand-alone application, rather than an excel file. This would greatly improve the user interface and create the possibility to include the technical library and information from the manual directly in the tool.

One of the weaknesses of the developed model, the inability to deal with compound lines, can be solved in the T-TIST. The regional corridor can be divided into sections, which can be assessed individually. This enables the tool to indicate that certain sections could be transformed into class C lines, while other sections should become class A. Moreover, this would also create the possibility to assess sections with different track layouts.

The usability of the suitability scan can be improved by including the possibility to store and compare the results of previous runs. This will be a useful feature when the most suitable route is studied. Besides the rough capacity analysis, a travel time analysis can be included in the T-TIST. This provides additional insight in the possible benefits of a tram-train line.

10 References

2getthere. (2018). *Rivum Business Park.* Retrieved from: https://www.2getthere.eu/projects/rivium-business-park/, 26 June 2018.

Allen, P. & Bevan, A. (2008). *Determination of Tramway Wheel and Rail Profiles to Minimise Derailment.* Manchester Metropolitan University. 12 February 2008.

Arcadis. (2003). *Risicoanalyse overwegen lightrailproef Gouda – Alphen aan den Rijn.* Amersfoort, January 2003.

Arcadis. (2004). *Revisiedocument veiligheidsstudie lightrailproef Gouda – Alphen aan den Rijn.* Amersfoort, April 2004.

AVG. (2015). *TramTrain connects town and country.* Albtal-Verkehrs-Gesellschaft GmbH, Karlsruhe.

Baker, J. (2018). *iLint: The world's first hydrogen-powered train.* Railway Technology, 22 January 2018.

Balcombe, R., Mackett, R., Paulley, N., Preston, J., Shires, J., Titheridge, H., … White, P. (2004). *The demand for public transport: a practical guide*. TRL Report TRL593.

Bigot, J. (2014). *Questions autour d'une « différenciation ».* 20 minutes. 26 June 2013.

Boenke, D. & Girnau, G. (2014). *Stadtbahnsysteme.* Verband Deutscher Verkehrsunternehmen (VDV). Eurailpress, Hamburg.

Breng. (n.d.). *Breng Flex.* Retrieved from: https://www.breng.nl/brengflex/1411, 05 October 2018.

Briggs, R. (2018). *[Personal interview tram-train and rail projects around Cardiff, UK].*

Brand, J., Van Oort, N., Hoogendoorn, S.P. & Schalkwijk, B. (2017). *Modelling Multimodal Transit Networks. Integration of bus networks with walking and cycling.* Proceedings of IEEE MT-ITS conference, Napoli.

Bunschoten, T., Molin, E. & van Nes, R. (2013). *Tram or Bus; does the Tram Bonus exist?* Paper for the European Transport Conference 2013, Frankfurt, Germany.

Calthorpe, P. (1990). *Transit-Oriented Development Design Guidelines for the County of Sacramento.* Peter Calthorpe Associates, Sacramento, CA. September 1990.

Carroll, R. (2018). *UK Tram-Train Pilot. Lessons Learned.* Mott MacDonald, Altrincham, UK.

Ceder, A. (2007). *Public Transit Planning and Operation.* Taylor & Francis Group.

Crosbee, D., Allen, P.D. & Carroll, R. (2016). *Analysis of design and performance of tram-train profiles for dual-operation running.* Journal of Rail and Rapid Transit, Vol 231(5), pp578-597.

De Keizer, B. & Hofker, F. (2013). *Klantwaardering van Overstappen.* Paper presented at the Colloquium Vervoersplanologisch Speurwerk, Rotterdam.

De Vos, P. (2016). *Railway Noise in Europe. State of the art report.* UIC, Paris. March 2016.

Djoko, E. (2018) *[Personal interview tram-train Karlsruhe].*

Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). *Multi-criteria analysis: a manual.*

Donders, M. (2018) *[Personal interview Uithoflijn & tram-train]*.

EC. (2018). *Speed limits.* European Commission. Retrieved from http://ec.europa.eu/transport/road_safety/going_abroad/netherlands/speed_limits_en.htm

EEA. (2017). *Greenhouse gas emissions from transport.* European Environment Agency. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-10

EPA. (2018) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2016.* U.S. Environmental Protection Agency.

ERA. (2015). *Guide for the application of the INF TSI.* European Railway Agency, Valenciennes, France.

Gemeente Amsterdam. (2017). *Noord/Zuidlijn. Verslag nr. 94.* Gemeente Amsterdam, Metro en Tram. Verslag 3^{e} kwartaal 2017.

Gibson, G., Milnes, R., Morris, M. & Hill, N. (2011). *Rail Transport*. IEA ETSAP Technology Brief T11 – January 2011.

Godziejewski, B. (2018). *[Personal interview technical solutions tram-train].*

Goverde, R. (2016). *Railway Operations II. Railway capacity planning.* CIE4811 Lecture, TU Delft.

Haarsman, G. (2012). *De weerstand van overstappen.* MSc thesis, Universiteit Twente.

Haering, P. (2018) *[Personal interview technical solutions tram-train].*

Hupkes, G. (1982). *The law of constant travel time and trip-rates.* Futures, Vol 14, Iss 1, pp 38-46. February 1982.

HiTrans. (2005). *Public Transport – Planning the Networks.* HiTrans Best practice guide 2

ITDP. (2014). *What is BRT?* Institute for Transportation & Development Policy.

Janić, M. (2014) *Advanced Transport Systems: Analysis, Modeling, and Evaluation of Performances.* Springer-Verlag, London.

Karr, M. (1998). *Mehrsystemkonzepte der Schienenbahnen in Europa.* Retrieved from: http://www.karr.de/veroeffentlichungen/#_Toc430326045, 13/06/2018

Kats, T. (2018). *[Personal interview Hoekse Lijn].*

Kay, D., Morris, M. & Hill, N. (2011). *Public Transport.* IEA ETSAP Technology Brief T10 – January 2011.

KiM. (2017). *Verdeling vervoerwijzen in het voor- en natransport naar en van belangrijkste Nederlandse treinstations, 2005-2014.* Mobiliteitsbeeld 2017. Kennisinstituut voor Mobiliteitsbeleid, Den Haag.

Kruszelnicki, K.S. (2012). *How dangerous is rubber dust?* ABC Science, 31 July 2012.

Kühn, A. (2007). *TramTrain and its safety issues – experiences and approaches.* Jernbanetilsynet Seminar. Oslo, 17/10/2007.

Kühn, A. (2018). *[Personal interview on tram-train].*

Landex, A., Kaas, A. H., Schittenhelm, B., & Schneider-Tilli, J. (2006). *Evaluation of railway capacity.* In Proceedings of Trafficdays

Metro Report. (2012). *Chemnitz orders electro-diesel tram-trains.* Metro Report International (online), 15 August 2012.

Metro Report. (2018). *Keolis tests autonomous electric shuttle in Belgium.* Metro Report International (online), 5 September 2018.

Metrobits. (2018). *World Metro Database.* Retrieved from http://mic-ro.com/metro/table.html, 28/06/2018.

Milakis, D. & Van Wee, B. (2018) *"For me it is always like half an hour": Exploring the acceptable travel time concept in the US and European contexts.* Transport Policy 64, pp 113-122.

Mott MacDonald. (2016). *RandstadRail Performance Review.* Arnhem, January 2016.

Muller, A. (2015). *Toegankelijkheid in de 'Haagse Polder'* Nationaal Verkeerskundecongres 2015.

Naegeli, L., Weidmann, U. & Nash, A. (2012). *Checklist for Successful Application of Tram-Train Systems in Europe*. Transportation Research Record: Journal of the Transportation Research Board, No 2275, pp 39-48.

Novales, M. & Conles, E. (2012). *Cádiz Bay tram-train: the first experience over Spanish conventional tracks.* 92nd Transportation Research Board Annual Meeting, Washington D.C.

NS. (2018). *Groene stroom.* Retrieved from: https://www.ns.nl/over-ns/duurzaamheid/energie/groene-stroom.html, 25/05/2018.

NVV. (2006). *RegioTram. Our advanced rail scheme for the Kassel region.* Nordhessischer VerkehrsVerbund. Kassel.

NVV. (2016). *RegioTram. Präsentation für die Delegation aus dem Kreis Darmstadt-Dieburg.* Nordhessischer VerkehrsVerbund. Kassel.

Ov-bureau GD. (2017). *Bestek Aanbesteding Concessie Groningen Drenthe 2020.* OV-bureau Groningen Drenthe, 4 december 2017.

OVPro. (2018). *HTM overweegt verplaatsen incheck-palen naar tramhalte.* Retrieved from: https://www.ovpro.nl/tram/2018/05/25/htm-overweegt-verplaatsen-incheck-palen-naar-tramhalte/, 31/05/2018.

OvV. (2008) *Ontsporingen bij RandstadRail.* Onderzoeksraad voor de veiligheid. Den Haag. November 2008.

Pachl, J. (2014). *Timetable Design Principles.* In: Railway Timetabling & Operations, Ch2. Eds Pachl, J. & Hansen, I.A. Eurailpress, Hamburg.

PBL. (2009). *Openbaar vervoer, ruimtelijke structuur en flankerend beleid: de effecten van beleidsstrategieën.* Planbureau voor de Leefomgeving.

Perez, M. (2004). *Karlsruhe Model.* TransportTechnologie-Consult Karlsruhe GmbH.

PNH. (2015). *Nota van uitgangspunten OV-concessie Noord-Holland Noord.* Provincie Noord-Holland, NL, 17 november 2015.

ProRail. (2018). *Recordaantal treinkilometers in nieuwe dienstregeling 2019.* ProRail, 20 August 2018.

PZH. (2006). *Eindrapport Lightrailproef RijnGouwelijn.* Provincie Zuid-Holland. Den Haag, December 2006.

Railway Technology. (2018). *Rijn Gouwelijn Rail Project in Netherlands from ProRail.* Retrieved from: https://www.railway-technology.com/projects/rijngouwlijn/, 22 August 2018.

Railway Techonology. (2018a). *Sytral places order for 11 Citadis trams.* Railway Technology (online), 11 September 2018.

Railwaygazette. (2007). *Paris projects prosper despite diversity.* Railwaygazette (online), 26 October 2007.

Railwaygazette. (2014). *Nantes - Châteaubriant tram-train launches this month.* Railwaygazette (online), 17 February 2014.

Railwaygazette. (2015). *NS confirms direct order for 58 Stadler EMUs.* Railwaygazette (online), 23 April 2015.

Redman, L., Friman, M., Gärling, T. & Hartig, T. (2013). *Quality attributes of public transport that attract car users: a research review.* Transport Policy 25 (2012), pp119-127.

RSSB. (2014). *GK/GN0628 Guidance on Infrastructure Based Train Detection Interface Requirements.* RSSB, London. Issue 2, December 2014.

SNCF. (2018). *Horaires T2 Nantes – Vertou – Clisson.* Version 23-8-2018.

SNCF. (2018a). *Horaires T1 Nantes – Nort-sur-Erdre – Châteaubriant.* Version 7-7-2018.

Stadler. (n.d.) *Citylink tram train. Verkehrsverbund Mittelsachsen (VMS), Chemnitz, Germany.*

Stadler. (2018) *[Short interview on cab design of tram-train vehicles].*

Siemens. (2016). *Avenio – fits your city.* Siemens Mobility Division, Munich, Germany.

Steer Davies Gleave. (2018). *LRT versus BRT: which is the better option?* Retrieved from: http://www.steerdaviesgleave.com/news-and-insights/LRT-versus-BRT, 17/05/2018.

Streeter, T. (2010). *Kassel: A city committed to tram-trains.* Tramways and Urban Transit, no 865, pp23-26. January 2010.

Streeter, T. (2018). *Creating a Tram-Train 'Standard'.* Tramways and Urban Transit, no 968, pp294-295. August 2018.

T4. (no date). *T4 Jusqu'à Clichy-sur-Bois, Montfermeil. FAQ.* Retrieved from: http://faq.tramway-t4.fr, 10-07-2018.

TAUT. (2017). *Tram-trains to Rotherham edge ever closer…* Tramways and Urban Transit, no 953. May 2017.

Ten Heuvelhof, E., Koppenjan, J., Broekhans, B., Leijten, M., Veeneman, W. & van der Voort, H. (2008). *Het RandstadRail-project: lightrail, zware opgave. Onafhankelijk onderzoek RandstadRail Haagse Deel.* Technische Universiteit Delft, 26 februari 2008.

Teodorović, D. & Janić, M. (2016). *Public Transportation Systems.* In: Transportation Engineering; theory, practice and modelling. Ch7. Butterworth-Heinemann, Oxford.

Teule, O. & Rienstra, S. (2000). *Chain mobility without transfer. The integration of tram-train systems.* In: "Colloquium Vervoersplanologisch Speurwerk 2000: Wie betaalt bepaalt", pp245-262. Delft, CVS, 30 november en 1 december 2000.

The Economist. (2017). *Why Latin America is seeing a cable-car boom.* The Economist, 26 October 2017.

Thorpe, A. & Harrison, R.M. (2008). *Sources and properties of non-exhaust particulate matter from road traffic: A review*. Science of The Total Environment. Vol. 400, Issues 1-3, pp270-282. August 2008.

Tirachini, A., Sun, L., Erath, A. & Chakirov, A. (2016). *Valuation of sitting and standing in metro trains using revealed preferences.* Transport Policy, Vol. 47, pp94-104. April 2016.

TMH. (2018). *Troeven van de tram.* Tram Maastricht-Hasselt. De Lijn. Retrieved from: https://www.trammaastrichthasselt.eu/wiewatwaarom/tram-maastricht-hasselt-alleen-maar-troeven/, 29/05/2018.

Transilien. (2018). *Ligne T4.* Retrieved from: https://www.transilien.com/fr/lignes/tram/T4#frequence-circulations-ligne-t4-1599, 17/09/2018.

TRB. (2013). *Transit Capacity and Quality of Service manual, Third edition*. TCRP Report 165. Transportation Research Board, Washington, D.C.

Triantaphyllou, E. (2000). *Multi-criteria decision-making methods: A comparative study.* Kluwer Academic Publishers, Dordrecht.

Trillas, E. & Eciolaza, L. (2015). *Fuzzy Logic. An Introductory Course for Engineering Students.* Springer International Publishing AG, Switzerland.

UIC. (2013). *UIC Code 406.* UIC Leaflet, 2nd edition. June 2013.

UN-Habitat. (2013). *Planning and Design for Sustainable Urban Mobility.* Routledge, Oxon.

Van der Meijs, P.R. (2015). *Bus Rapid Transit. Establishment of a BRT design model to design and evaluate BRT configurations.* MSc Thesis. Delft University of Technology.

Van der Bijl, R. & Kühn, A. (2004). *Tramtrain: The 2nd generation. New criteria for the 'ideal tramtrain city'.* European Transport Conference 2004. Strasbourg.

Van der Bijl, R., Baartman, J. & van Witsen, M. (2010). *Uitweg uit de spraakverwarring. Definitie & begrippenkader Light Rail.*

Van der Bijl, R., Bukman, B. & van Oort, N. (2015). *Investeren in de stad; Lessen uit 47 light rail projecten.* Milete Media, Amsterdam.

Van der Bijl, R., van Oort, N. & Bukman, B. (2018). *Light Rail Transit Systems*. *61 Lessons in Sustainable Urban Development.* Elsevier, Amsterdam.

Van der Bijl, R. (2018). *[Personal interview tram-train and light rail].*

Van der Blij, F., Veger, J. & Slebos, C. (2010). *HOV op loopafstand: Het invloedsgebied van HOV-haltes.* Paper presented at the Colloquium Vervoersplanologisch Speurwerk, Roermond.

Van Nes, R. (2016) *Introduction and Urban Network design.* CIE4811 Lecture, TU Delft.

Van Oort, N. & Weeda, V.A. (2007). *Xpert + Xpert = 3. Wat kunnen trein- en tramexploitatie van elkaar leren.* In L. Berkhout (Ed.). De Xpert-factor. Bundeling van bijdragen aan het CVS (pp. 361-376). Rotterdam.

Van Oort, N. & van Nes, R. (2009). *Line length versus operational reliability.* Transportation Research Record Journal of the Transportation Research Board. December 2009.

Van Oort, N. (2011). *Service Reliability and Urban Public Transport Design.* TRAIL PhD Thesis Series, Delft.

Van Oort, N., Van der Bijl, R. & Roeske, R. (2014). *Light rail implementation: success and failure aspects of Dutch light rail projects.* 94th Transportation Research Board Annual Meeting, Washington D.C.

Van Oort, N., Van der Bijl, R. & Verhoof, F. (2017). *The wider benefits of high quality public transport for cities.* European Transport Conference, Barcelona.

Van Oort, N. (2018). *[Personal interview public transport governance].*

Veeneman, W. (2018). *Prorail moet plannen op een postzegel.* Trouw, 20 August 2018.

Veeneman, W. (2018a). *Nederland te vol voor extra spoor? Kijk verder dan de rails lang zijn.* Trouw, 25 August 2018.

VMS. (n.d.) *2002-2016 Das Chemnitzer Modell.* Verkehrsverbund Mittelsachsen GmbH, Chemnitz.

Vreeswijk, P. (2018) *[Personal interview Hoekse Lijn and RandstadRail].*

Vuchic, V.R. (2005). *Urban Transit. Operations, Planning and Economics.* John Wiley & Sons, Inc., Hoboken, New Jersey.

Vuchic, V.R. (2007). *Urban Transit. Systems and Technology.* John Wiley & Sons, Inc., Hoboken, New Jersey.

Wardman, M. (2001). *A Review of British Evidence on Time and Service Quality Valuations.* Transportation Research E, 37 2-3, pp107-128.

Wardman, M. (2004). *Public transport values of time.* Transport Policy 11, 2004, pp363-377.

Warman M. & Whelan, G. (2010). *20 years of rail crowding valuation studies: evidence and lessons from British experience.* 89th Transportation Research Board Annual Meeting, Washington D.C.

White, P. (2009). *Public Transport. Its planning, management and operation.* 5th edition. Routledge, Abingdon UK.

Wiercx, M., Huisman, R., Van Oort, N. & Van Arem, B. (2019). *Operations of zero-emission buses: impacts of charging methods and mechanisms on costs and the level of service.* 98th Transportation Research Board Annual Meeting, Washington DC.

Wikipedia. (2018) *Schema von U-bahn und S-bahn.* Retrieved from: https://commons.wikimedia.org/wiki/File:Shema_U-Bahn_S-Bahn.PNG

A. Public transport modes

This section briefly describes the main modes of public transport and provides the main operational and technical parameters.

A.1 Urban bus

A bus system is the most basic form of public transport. Buses can use the existing road network, which makes bus systems very flexible. It is easy to divert lines when necessary or desired and vehicles are available in different sizes, to suit transport demand. Besides, buses are relatively cheap, so bus systems have low capital expenditures (CAPEX) (Teodorović & Janić, 2016). However, bus systems on regular infrastructure are prone to congestion and are unable to offer high capacities. Most urban bus systems have dense stop spacing, which means that a bus stop will often be just around the corner. However, the large number of stops results in low operational speeds.

Most buses still run on diesel, which gives noise and exhaust fume pollution. However, electric buses are becoming more common. Even though battery capacity is improving, electric buses still require frequent charging.

Strengths:
- Flexible
- Cheap
- Does not require own infrastructure
- Dense stop spacing often results in low access times

Weaknesses:
- Prone to congestion
- Limited capacity
- Either diesel-powered or requires frequent charging

Table A-1: System parameters – Urban bus.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	15 - 20 km/h	Maximum speed	80 km/h	Track gauge	n.a.
Stop spacing	200 – 500 m	Vehicle length	12 m	Rail type	n.a.
Dwell time	10 s – 1 min	Vehicle width	< 260 cm	Platform height	180 mm
Line length	--	Vehicle weight	11 t	Driving regime	On sight
Network structure	Grid / Radial	Vehicle capacity	< 100 passengers	Overhead line height	n.a.
Peak capacity	1200 pphpd	Power supply	Diesel / battery	Points control	n.a.
Minimum headway	5 minutes / line	Crashworthiness	n.a.		
Degree of separation in traffic	ROW C	Floor height	190 – 300 mm		
Integration in city	Well integrated	Minimum curve radius	18 m		
		Acceleration / (emergency) deceleration	n.a.		

Source: Vehicle parameters are based on the VDL Citea SLE120.

A.2 Bus rapid transit (BRT)

Bus rapid transit systems can be defined as "*single vehicles mostly operating on separated bus lanes on corridors, often with priority at intersections. Service quality is of a high level, with high speeds and frequencies. Usage is comfortable.*" (ITDP, 2014). It is regarded as a cheaper alternative compared to rail systems but requires separate infrastructure for high speeds and frequencies. Building fully separated infrastructure in developed cities is expensive, and not much cheaper than building rail infrastructure. On the other hand, buses are much cheaper than rail vehicles (Steer Davies Gleave, 2018). To provide high capacities, fare collection should take place on stations rather than in-vehicle. This requires more complex stops (Van der Meijs, 2015).

Strengths:

- Capacity can be allocated in a highly flexible manner
- High speeds and capacities can be achieved

Weaknesses:

- Requires separated infrastructure for high reliability
- Building the required infrastructure is not necessarily much cheaper than rail infrastructure
- Metro-like stations required for high capacities
- Does not profit from the 'railbonus' (Bunschoten et al., 2013)

Table A-2: System parameters – Bus rapid transit.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	20 – 40 km/h	Maximum speed	80 - 100 km/h	Track gauge	n.a.
Stop spacing	300 – 2000 m	Vehicle length	18 m	Rail type	n.a.
Dwell time	10 – 30 s	Vehicle width	< 260 cm	Platform height	180 mm
Line length	--	Vehicle weight	16 t	Driving regime	On sight
Network structure	Radial / Tangential	Vehicle capacity	< 180 passengers	Overhead line height	n.a.
Peak capacity	36000 pphpd	Power supply	Diesel / battery	Points control	n.a.
Minimum headway	13 s	Crashworthiness	n.a.		
Degree of separation in traffic	ROW B/C	Floor height	190 – 300 mm		
Integration in city	Moderately integrated	Minimum curve radius	24 m		
		Acceleration / (emergency) deceleration	n.a.		

Source: Vehicle parameters are based on the single-articulated VDL Citea SLFA-180
Peak capacity and minimum headway are based on the Bogota BRT system.

A.3 Urban tram

Trams are the lightest and smallest form of rail-bound public transport. Tramways can be built segregated from roads, on grass strips in the median of large avenues, but tracks can also be embedded in the road surface, requiring no extra space. As trams can share the road with regular road vehicles, they are therefore equipped with braking and indicator lights and can achieve high emergency decelerations (relative to other rail vehicles). Tramways can be integrated in pedestrian areas, as the tracks in the pavement shows the presence of a tram.

Tramways are one of the oldest forms of public transport and exist in several old cities. As such, they were designed with small loading and track gauges. There are systems that still use high-floor vehicles, but gradually all are being replaced by modern, low-floor vehicles. This improves accessibility from low platforms (Boenke & Girnau, 2014). Tram vehicles are small compared to other forms of rail-bound public transport and have lower maximum speeds. Their capacity is larger than that of regular bus systems. Operational speeds of trams are generally low. In pedestrian areas, trams must drive at walking pace (<15 km/h) and they are prone to congestion on stretches where they share their infrastructure with regular road traffic (Teodorović & Janić, 2016).

Strengths:
- Environmentally friendly
- Very accessible / many stops and can easily be integrated in pedestrian areas
- Light vehicles, quick acceleration
- The ability of mixing with traffic leads to no additional space requirements
- Separated tramways can be built in grass lanes

Weaknesses:
- Prone to congestion in shared spaces
- Low operational speed
- Old systems cannot accommodate large vehicles
- Tram vehicles are more expensive than buses

Table A-3: System parameters – Urban tram.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	15 km/h	Maximum speed	< 70 km/h	Track gauge	1000 / 1435mm
Stop spacing	200 – 600 m	Vehicle length	< 35 m	Rail type	Grooved rail
Dwell time	< 30 s	Vehicle width	220 – 265 cm	Platform height	300 mm
Line length	5 – 20 km	Axle load	< 11.5 t	Driving regime	On sight
Network structure	Radial as backbone. Grid as feeder service.	Vehicle capacity	< 250 passengers	Overhead line height	> 4.7 m
Peak capacity	5000 pphpd	Power supply	600 / 750 V Overhead lines Battery	Points control	From vehicle
Minimum headway	5 minutes / line	Crashworthiness	> 200 kN		
Degree of separation in traffic	ROW B/C	Floor height	350 mm		
Integration in city	Well integrated	Minimum curve radius	20 m		
		Acceleration / (emergency) deceleration	1.3 / (> 2.5) 1.2 m/s^2		

Source: Operational parameters: Boenke & Girnau (2014); Van der Bijl et al. (2015);
Vehicle parameters: Alstom Citadis, Siemens Avenio.

A.4 Regional tram

According to Van der Bijl et al. (2015), the regional tram is an eminent example of light rail. Regional trams differ from real urban trams in that they can achieve higher average speeds and allow larger vehicles. The higher average speed is a result of regional trams running on separate infrastructure outside city centres and fast accelerations. Regional trams can be wider and longer than urban trams. However, when the regional trams are also used on old urban systems, dimensions can still be limited.

Van der Bijl et al. (2015) note that regional street-level trams can provide additional accessibility to public areas. It can serve these areas with several stops, whereas a metro would only serve a single station.

Strengths:

- Separated infrastructure, which increases reliability
- Combines features of urban trams in city centres with higher speeds outside the centre

Weaknesses:

- Fewer stops
- Old urban tram networks might restrict the use of larger vehicles

Table A-4: System parameters – Regional tram.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	30 – 45 km/h	Maximum speed	80 km/h	Track gauge	1435 mm
Stop spacing	0.4 – 2 km	Vehicle length	25 – 75 m	Rail type	Grooved / Vignole
Dwell time	< 30 s	Vehicle width	< 265 cm	Platform height	300 mm
Line length	10 – 40 km	Axle load	< 11.5 t	Driving regime	On sight / protected
Network structure	Radial	Vehicle capacity	< 500 passengers	Overhead line height	> 4.7 m
Peak capacity	14000 pphpd	Power supply	600 / 750 V Overhead lines	Points control	From vehicle / via interlocking
Minimum headway	3 min / line	Crashworthiness	> 400 kN		
Degree of separation in traffic	ROW A/B	Floor height	350 mm		
Integration in city	Moderately integrated	Minimum curve radius	20 m		
		Acceleration / (emergency) deceleration	1.3 / (> 2.5) 1.2 m/s^2		

Source: Operational parameters: Boenke & Girnau (2014); Van der Bijl et al. (2015).
Vehicle parameters: Alstom Citadis, CAF Urbos.

A.5 Metro

Metro systems are the backbone of public transport in many large cities. Metro systems are fully separated from other infrastructure. In city centres, metro systems are mostly situated underground, while in suburbs lines run on viaducts. In some systems, all lines have their own infrastructure (tracks, platforms), with limited to no connections between them. The fully separated and line-specific infrastructure makes operations very reliable and very high capacities can be achieved. Headways of less than 2 minutes are possible on (semi-) automated systems (London Victoria Line) and vehicles generally have capacities of up to 1000 passengers. In some systems, train capacities can reach up to 2000 passengers at maximum crush capacity. Vehicles have many doors and are designed to accommodate many standing passengers. Platform and vehicle heights are matched, which greatly increases boarding and alighting speed.

Due to the fully separated nature, extensions are very expensive. Especially in dense urban areas, adding new links can cost hundreds of millions per kilometre. An example of such recent extensions is the Noord-Zuidlijn in Amsterdam (€325m/km (Gemeente Amsterdam, 2017)).

Strengths:

- High capacity
- Closed system, high reliability
- Many doors and level boarding, allowing for short dwell times

Weaknesses:

- Very expensive (especially CAPEX; automated trains have lower OPEX)
- Difficult to construct in highly-developed cities

Table A-5: System parameters – Metro.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	30 km/h	Maximum speed	80 km/h	Track gauge	1435 mm
Stop spacing	0.4 – 1.6 km	Vehicle length	50 – 150 m	Rail type	Vignole
Dwell time	< 30 s	Vehicle width	220 – 300 cm	Platform height	Level w/ floor
Line length	5 – 30 km	Axle load	< 17.5 t	Driving regime	Protected
Network structure	Radial, tangential	Vehicle capacity	< 2000 passengers	Overhead line height	n.a.
Peak capacity	75000 pphpd	Power supply	750 V, 3rd rail	Points control	Via interlocking
Minimum headway	1.5 min	Crashworthiness	> 800 kN		
Degree of separation in traffic	ROW A	Floor height	> 750 mm		
Integration in city	Closed	Minimum curve radius	> 120 m		
		Acceleration / (emergency) deceleration	1.0 / 1.15 m/s^2		

Source: Operational parameters: Van der Bijl et al., (2015)
Vehicle parameters: Tyne and Wear Metro.

A.6 Regional heavy rail (S-bahn)

Regional rail (S-bahn / commuter rail) uses heavy rail infrastructure and stations. Vehicles are heavier than those used on metro lines, with lower acceleration and braking rates, but higher maximum speeds. Therefore, station spacing is generally larger than that of metros. However, modern trains are lighter and therefore capable of achieving faster accelerations (allowing shorter stop spacings) (Van der Bijl, 2018). Services are frequent, but capacity is limited if double tracks are shared with services with different stopping patterns (i.e. express services) (White, 2009). The focus of regional rail is transporting people of neighbouring towns and outskirts of cities towards centres and transfer hubs.

Strengths:

- High speeds
- Provide good connections between cities and urban region
- On separate tracks, very high capacities can be achieved
- Stations serve as transfer hubs to local public transport

Weaknesses:

- Can be less accessible (especially for disabled) due to height differences between platform and vehicle, although modern vehicles are designed with level entry
- Larger stop spacing and only single corridors in towns, lengthening access and egress times
- Combined operation with express services limits maximum frequency (and thus capacity)

Table A-6: System parameters – Regional heavy rail.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	> 60 km/h	Maximum speed	> 100 km/h	Track gauge	1435 mm
Stop spacing	2 – 5 km	Vehicle length	50 – 200 m	Rail type	Vignole
Dwell time	1 min	Vehicle width	< 315 cm	Platform height	550/760 mm
Line length	> 20 km	Axle load	< 21 t	Driving regime	Protected
Network structure	Radial	Vehicle capacity	< 1500 passengers	Overhead line height	5.5 m
Peak capacity	--	Power supply	> 1.5kV Overhead lines Diesel	Points control	Via interlocking
Minimum headway	2.5 min	Crashworthiness	> 1500 kN		
Degree of separation in traffic	ROW A	Floor height	> 760 mm		
Integration in city	Separated	Minimum curve radius	> 180 m		
		Acceleration / (emergency) deceleration	0.6 – 1.0 / 0.8 – 1.2 m/s^2		

Source: Operational parameters: Van der Bijl et al. (2015).
Notes: Headway minimum between two consecutive trains. Vehicle width and height are as limited by the UIC GC loading gauge.

A.7 Intercity heavy rail, high speed rail

Intercity and high-speed rail are the main modes for interregional and (inter)national passenger transport. Generally, all passengers are seated, and vehicles provide high levels of comfort. Trains only call at large stations, which enables high speeds. On high-volume routes, double-deck carriages are used. In the Netherlands, double-deck intercity trains with lengths of 10 carriages and seating capacities of 1000 passengers are commonly used during peak hour (NS). Japanese Shinkansen high-speed trains have up to 16 carriages (Wikipedia).

Strengths:
- High capacity
- Fast
- Comfortable

Weaknesses:
- Less accessible (especially for disabled) due to height differences between platform and vehicle
- Long dwell times due to limited number of doors
- Few stops, small direct catchment area

Table A-7: System parameters – Intercity heavy rail.

Operational Parameters		Technical parameters - Vehicle		Technical parameters - Infra	
Average speed	> 80 km/h	Maximum speed	> 100 km/h	Track gauge	1435 mm
Stop spacing	> 10 km	Vehicle length	> 100 m	Rail type	Vignole
Dwell time	< 3 min	Vehicle width	< 315 cm	Platform height	550/760 mm
Line length	> 50 km	Axle load	<22.5 t	Driving regime	Protected
Network structure	City-to-city	Vehicle capacity	< 2000 passengers	Overhead line height	5.5 m
Peak capacity	--	Power supply	> 1.5kV Overhead lines Diesel	Points control	Via interlocking
Minimum headway	2.5 min	Crashworthiness	> 1500 kN		
Degree of separation in traffic	ROW A	Floor height	> 760 mm		
Integration in city	Separated	Minimum curve radius	> 180 m		
		Acceleration / (emergency) deceleration	0.6 – 1.0 / 0.8 – 1.2 m/s^2		

Notes: Vehicle width as limited by the UIC GC loading gauge. Headway minimum between two consecutive trains.

B. Tram-train system parameters

This section provides the system parameters of the tram-train networks investigated in chapter 4. Lines are treated separately. The tables are split into three sections: the tram-train general parameters, and parameters that hold for the train and tram part. For several systems, network maps are provided, to give an impression of the regional spread of tram-train lines. Table B-1 gives an overview of the parameters treated, and how they are interpreted for the different parts of the system.

The average stop spacing for a full line is calculated by dividing the line length by the total number of stops minus one (to get the spacing). See equation (4). When changeover happens at a train station, this station is counted in the tram network. For the stop spacing on the train network, the length is divided by the number of stations.

$$spacing = \frac{length_{section}}{n_{stops} - 1} \qquad (4)$$

The average speed and trip times are based on the September 2018 timetables where possible. Line speeds for the German networks are derived from the DB Netze Infrastrukturregister. Line lengths have been determined with Google Maps. Vehicle data is retrieved from datasheets of manufacturers.

Table B-1: Explanation of system parameters.

Parameter	Tram-train	Train	Tram
Line length	Total line length	Length of the (shared) section on heavy rail	Length of the (shared) section on tram lines
Stops (av. spacing)	Total number of stops (average spacing between stops)	Number of stations on heavy rail section (average spacing)	Number of stops on tram section (average spacing)
Frequency	Frequency of the tram-train service	Frequency of other trains on the line + frequency of the tram-train	Maximum frequency on the busiest section
Max (average) speed	Max vehicle speed (average speed over the full line)	Line speed (average t-t speed on the heavy rail section)	Max speed on tram network (average t-t speed on the tram section)
Trip time	Total time from end to end	Time spend on heavy rail	Time spend in tram network
Power supply	Options for t-t	Power supply on heavy rail	Power supply on tram network
Platform/entry height	Entry height(s) of vehicle	Platform height t-t stations	Platform height t-t stops

B.1 Karlsruhe

The following tables and Figure B-1 give an overview of the Karlsruhe Stadtbahn network. The network consists of more lines than analysed below, but these lines give the best impression of tram-train. The border between EBO and BOStrab regulated operation is adhered to as much as possible. Some lines consist of two train and/or tram sections. Each of those is analysed separately. The parameters do not reflect the full lines S4, S5 and S8. These lines are longer than realistic for an urban region and analysed until the border of the KVV tariff area.

Except for lines S1 and S4, which are class C, all analysed lines are class A. Line S1 is the original Albtalbahn, the first tram-train line. This line is electrified at 750V and does not have shared operations. However, both ends of the line are operated under EBO regulation, making it a tram-train operated line. Line S4 use a large section EBO regulated and 15kV AC electrified line but does not have planned shared operations.

Line S2 is fully operated as tram under BOStrab regulation, while lines S6, S71, S81 and S9 are only operated on heavy rail lines under EBO regulation. Therefore, these lines are not analysed.

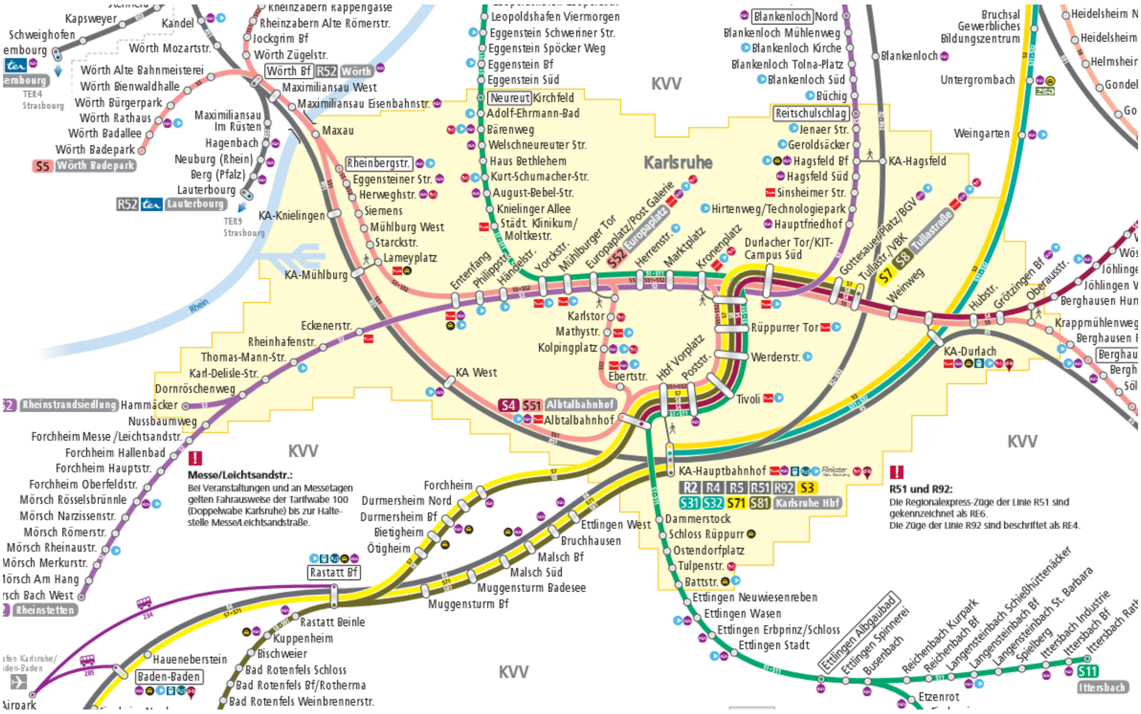


Figure B-1: Excerpt of the Karlsruhe Stadtbahn network. AVG.

Table B-2: Karlsruhe S1 (Bad Herrenalb – Hochstetten, Class C) parameters.

Parameter	Tram-train	Train – South	Train – North	Tram
Length	44 km	25 km	12 km	6.6 km
Stops (av. spacing)	54 (0.8 km)	18 (1.5 km)	18 (0.7 km)	18 (400 m)
Frequency	6 tph	6 tph	6 tph	28 tph
Max (av.) speed	80 (27) km/h	80 (41) km/h	80 (23) km/h	50 (14) km/h
Trip time	98 minutes	37 minutes	32 minutes	29 minutes
Power supply	750V	750V	750V	750V
Platform/entry height	340 mm	340 mm	340 mm	Curb / 340 mm

Table B-3: Karlsruhe S4 (Albtalbahnhof – Eppingen, Class C) parameters.

Parameter	Tram-train	Train	Tram
Line length	50 km	41 km	8.5 km
Stops (av. spacing)	36 (1.4 km)	22 (1.9 km)	14 (650 m)
Frequency	3 tph	0 + 3 tph	28 tph
Max (average) speed	100 (39) km/h	100 (48) km/h	50 (20) km/h
Trip time	76 minutes	51 minutes	25 minutes
Power supply	750V / 15kV AC	15kV AC	750V DC
Platform/entry height	580 mm	550 mm	Curb / 340 mm / 550 mm

Notes: Not all trains run the full line. 1 tph runs as Eilzug (fast service, takes 69 minutes), the other 2 tph call at all stations.

Table B-4: Karlsruhe S5 (Wörth Badepark – Pforzheim) parameters.

Parameter	Tram-train	Train - West	Train – East	Tram – Wörth	Tram – Karlsruhe
Line length	45 km	4.7 km	23 km	2.4 km	14.8 km
Stops (av. spacing)	49 (0.9 km)	5 (1.2 km)	16 (1.5 km)	5 (600m)	23 (650 m)
Frequency	6 tph	3 + 6 tph	2 + 6	3 tph	30 tph
Max (average) speed	100 (29) km/h	120 (35) km/h	160(36) km/h	50 (24) km/h	50 (23) km/h
Trip time	94 minutes	8 minutes	38 minutes	6 minutes	38 minutes
Power supply	750V / 15kV AC	15kV AC	15kV AC	750V DC	750V DC
Platform/entry height	580 mm	550 mm	550 mm	550 mm / 340 mm	Curb / 340 mm / 580 mm

Note: Not all trains run the full line.

Table B-5: Karlsruhe S51 (Germersheim – Albtalbahnhof) parameters.

Parameter	Tram-train	Train	Tram
Line length	44 km	40 km	3.7 km
Stops (av. spacing)	33 (1.4 km)	19 (2.2 km)	14 (300m)
Frequency	1 tph	3 + 6 tph	28 tph
Max (average) speed	100 (34) km/h	120 (44) km/h	50 (11) km/h
Trip time	77 minutes	54 minutes	21 minutes
Power supply	750V DC / 15kV AC	15 kV AC	750V DC
Platform/entry height	580 mm	550 mm	Curb / 380 mm / 550 mm

Note: S51 and S52 together provide half-hourly services between Germersheim and Wörth.

Table B-6: Karlsrhe S52 (Germersheim – Albtalbahnhof) parameters.

Parameter	Tram-train	Train	Tram
Line length	41.5 km	31.5 km	11.5 km
Stops (av. spacing)	34 (1.3 km)	16 (2.1 km)	18 (600 m)
Frequency	1 tph	3 + 6 tph	28 tph
Max (average) speed	100 (38) km/h	120 (47) km/h	50 (24) km/h
Trip time	65 minutes	40 minutes	25 minutes
Power supply	750V DC / 15kV AC	15kV AC	750V DC
Platform/entry height	580 mm	550 mm	Curb / 380 mm / 550 mm

Note: S51 and S52 together provide half-hourly services between Germersheim and Wörth.

Table B-7: Karlsruhe S7 (Karlsruhe Tullastraße – Achern) parameters.

Parameter	Tram-train	Train	Tram
Length	53 km	49 km	4 km
Stops (av. spacing)	23 (2.4 km)	13 (4 km)	10 (450 m)
Frequency	1 tph	*Unknown*	28 tph
Max (average) speed	100 (47) km/h	160 (59) km/h	50 (15) km/h
Trip time	68 minutes	50 minutes	16 minutes
Power supply	750V DC / 15kV AC	15kV AC	750V DC
Platform/entry height	580 mm	550 mm	Curb / 380 mm / 550 mm

Table B-8: Karlsruhe S8 (Karlsruhe Tullastraße – Schönmünzach) parameters.

Parameter	Tram-train	Train	Tram
Length	60 km	56 km	4 km
Stops (av. spacing)	38 (1.6 km)	28 (2 km)	10 (450 m)
Frequency	1	*Unknown*	28 tph
Max (average) speed	100 (39) km/h	160 (45) km/h	50 (15) km/h
Trip time	92 minutes	74 minutes	16 minutes
Power supply	750V DC / 15kV AC	15kV AC	750V DC
Platform/entry height	580 mm	550 mm	Curb / 380 mm / 550 mm

Note: Additional fast services run every two hours. These take 80 minutes and serve 9 stations. Together with S81, a half-hourly service is provided along parts of the line.

B.2 Kassel

The following tables give an overview of the system parameters of the RegioTram network in Kassel. For RT4, the frequency of 2 trains per hour is between Kassel and Zierenberg. The last part towards Wolfhagen is served once per hour. Figure B-2 shows the network and transfers to regional trains. RT 4 and 5 are secondary lines to the regional trains, while RT1 is the main mode.

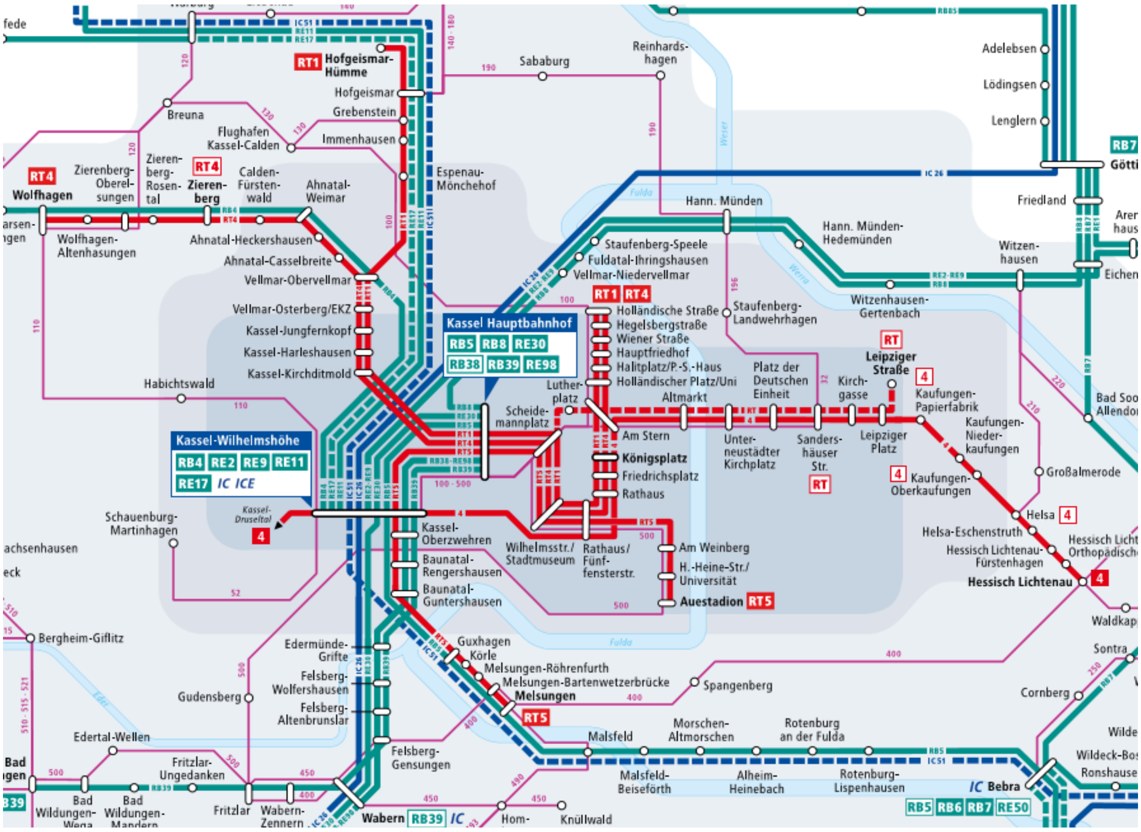


Figure B-2: RegioTram and regional train services around Kassel. NVV.

Table B-9: Kassel RT1 (Kassel – Hofgeismar) parameters.

Parameter	Tram-train	Train	Tram
Line length	35 km	30 km	5 km
Stops (av. spacing)	24 (1.5km)	10 (3km)	14 (350m)
Frequency	2 tph	1 + 2 tph	28 tph
Max (average) speed	100 (36) km/h	160 (49) km/h	50 (15) km/h
Trip time	59 minutes	37 minutes	20 minutes
Power supply	15kV AC / 600V DC	15kV AC	600V DC
Platform/entry height	360 mm	350 mm / 550 mm	240 mm

Source: NVV, 2016.

Table B-10: Kassel RT4 (Kassel – Wolfhagen) parameters.

Parameter	Tram-train	Train	Tram
Line length	36 km	31 km	5 km
Stops (av. spacing)	28 (1.3 km)	14 (2.2 km)	14 (350m)
Frequency	2 tph	1 + 2 tph	28 tph
Max (average) speed	100 (32) km/h	100 (40) km/h	50 (15) km/h
Trip time	68 minutes	47 minutes	20 minutes
Power supply	Diesel / 600V DC	Diesel	600V DC
Platform/entry height	360 mm	350 mm / 550 mm	240 mm

Source: NVV, 2016.

Table B-11: Kassel RT5 (Kassel – Melsungen) parameters.

Parameter	Tram-train	Train	Tram
Line length	31 km	28 km	3 km
Stops (av. spacing)	16 (1.9 km)	9 (3.1 km)	7 (400m)
Frequency	2 tph	4 + 2 tph	10 tph
Max (average) speed	100 (40) km/h	160 (48) km/h	50 (18) km/h
Trip time	47 minutes	35 minutes	10 minutes
Power supply	15kV AC / 600V DC	15kV AC	600V DC
Platform/entry height	360 mm	350 mm / 550 mm	240 mm

Source: NVV, 2016.

B.3 Chemnitz

The following tables give an overview of the system parameters of the Citybahn network in Chemnitz. Figure B-3 shows the network and transfers to regional trains.

Table B-12: Chemnitz C11 (Hauptbahnhof – Stollberg, Class C) parameters.

Parameter	Tram-train	Train	Tram
Line length	23.1 km	16.3 km	6.8 km
Stops (av. spacing)	27 (0.9 km)	11 (1.6 km)	16 (450 m)
Frequency	2 tph	0 + 2 tph	23 tph
Max (average) speed	80 (28) km/h	80 (44) km/h	60 (20) km/h
Trip time	49 minutes	22 minutes	21 minutes
Power supply	600/750V	750V DC	600V DC
Platform/entry height	300 mm entry	200 mm	200 mm

Source: https://www.city-bahn.de/de/Daten_Fakten/Unsere_Linien_1102.html

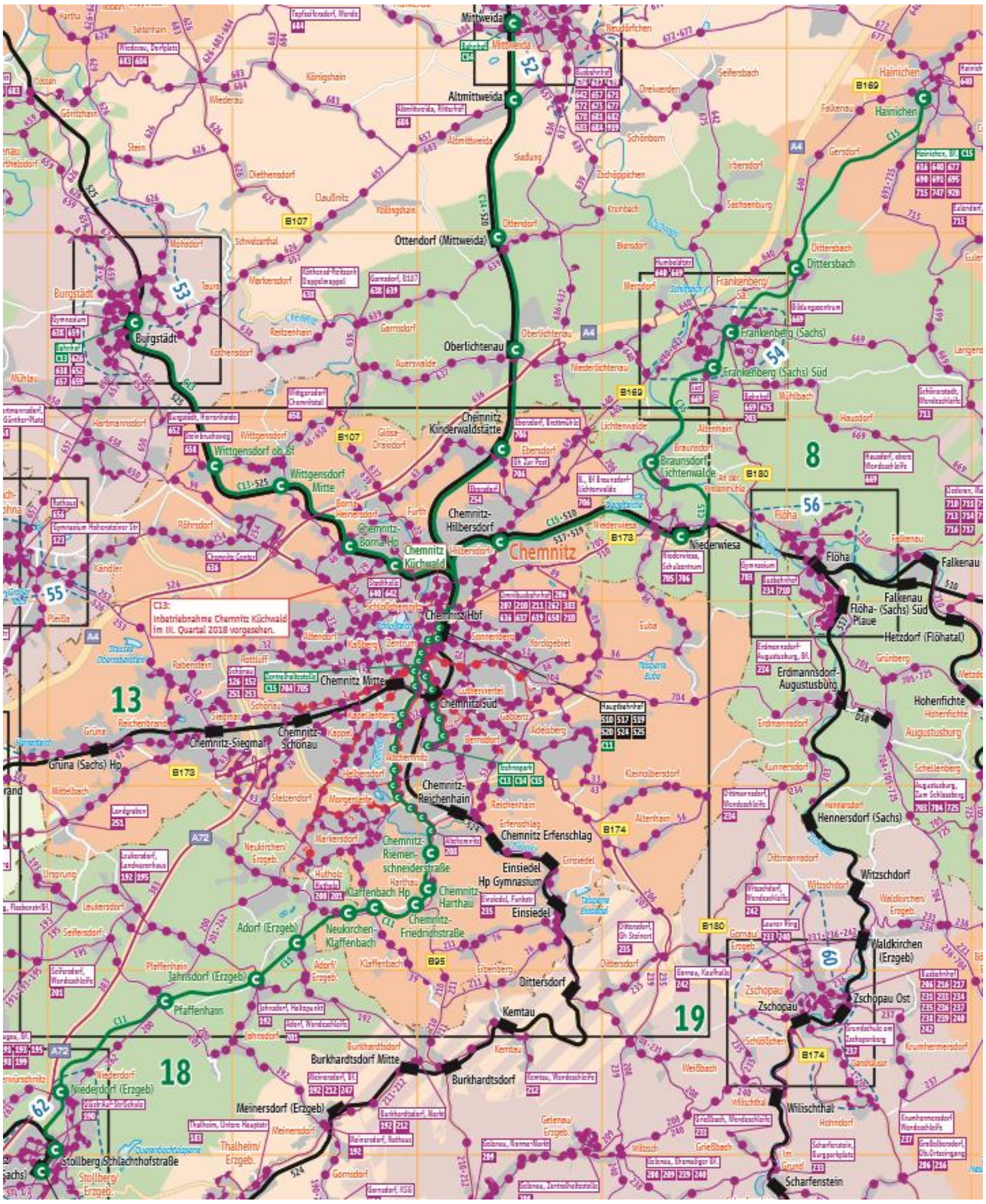


Figure B-3: Citybahn and regional rail network around Chemnitz. VMS.

Table B-13: Chemnitz C13 (Technopark – Burgstadt) parameters.

Parameter	Tram-train	Train	Tram
Line length	19.1 km	14.7 km	4.3 km
Stops (av. spacing)	16 (1.3 km)	6 (2.5 km)	10 (450 m)
Frequency	1 tph	1 + 1 tph	23 tph
Max (average) speed	100 (31) km/h	120 (52) km/h	60 (17) km/h
Trip time	37 minutes	17 minutes	15 minutes
Power supply	600/750V / Diesel	Diesel	600V DC
Platform/entry height	405 / 570 mm	550 mm	200 / 380 mm

Source: https://www.city-bahn.de/de/Daten_Fakten/Unsere_Linien_1102.html

Table B-14: Chemnitz C14 (Technopark – Mittweida) parameters.

Parameter	Tram-train	Train	Tram
Line length	22.1 km	17.8 km	4.3 km
Stops (av. spacing)	16 (1.5 km)	6 (3 km)	10 (450 m)
Frequency	1 tph	1 + 1 tph	23 tph
Max (average) speed	100 (36) km/h	100 (56) km/h	60 (17) km/h
Trip time	37 minutes	19 minutes	15 minutes
Power supply	600/750V / Diesel	15 kV AC	600V DC
Platform/entry height	405 / 570 mm	550 mm	200 / 380 mm

Source: https://www.city-bahn.de/de/Daten_Fakten/Unsere_Linien_1102.html

Table B-15: Chemnitz C15 (Technopark – Hainichen) parameters.

Parameter	Tram-train	Train	Tram
Line length	30.2 km	25.9 km	4.3 km
Stops (av. spacing)	18 (1.8 km)	8 (3.2 km)	10 (450 m)
Frequency	1 tph	5 + 1 tph	23 tph
Max (average) speed	100 (38) km/h	120/80 (52) km/h	60 (17) km/h
Trip time	48 minutes	20 minutes	15 minutes
Power supply	600/750V / Diesel	15 kV AC / Diesel	600V DC
Platform/entry height	405 / 570 mm	550 mm	200 / 380 mm

Source: https://www.city-bahn.de/de/Daten_Fakten/Unsere_Linien_1102.html

B.4 Nordhausen

Table B-16: Nordhausen parameters.

Parameter	Tram-train	Train	Tram
Line length	14.6 km	11.4 km	3.2 km
Stops (av. spacing)	21 (0.7 km)	12 (1 km)	9 (400 m)
Frequency	1 tph	< 1 + 1 tph	13 tph
Max (average) speed	50 (23) km/h	50 (31) km/h	50 (18) km/h
Trip time	38 minutes	22 minutes	11 minutes
Power supply	600V / diesel	Diesel	600V
Platform/entry height	300 mm	300 mm	300 mm

Source: Stadtwerke-nordhausen.de

B.5 Tram-train Mulhouse – Vallée de la Thur

Figure B-4 shows the tram-train line in the tram network of Mulhouse. Line 3 is the dark green line, which runs as additional service along the tram-train alignment.

Table B-17: Mulhouse parameters.

Parameter	Tram-train	Train	Tram
Line length	22 km	15 km	7 km
Stops (av. spacing)	18 (1.3 km)	7 (2 km)	11 (700 m)
Frequency	2 tph	1+2 tph	14 tph / 24tph (one stop)
Max (average) speed	100 (29) km/h	100 (36) km/h	50 (21) km/h
Trip time	46 minutes	25 minutes	20 minutes
Power supply	Dual-mode	25kV AC	750V DC
Platform/entry height	Low-floor	Low-floor	Low-floor

Figure B-4: Mulhouse tram network with tram-train line. Solea.

B.6 Sheffield – Rotherham

Table B-18: Sheffield – Rotherham parameters.

Parameter	Tram-train	Train	Tram
Line length	12 km	5 km	7 km
Stops (av. spacing)	14 (0.9 km)	2 (2.5 km)	12 (600 m)
Frequency	3 tph	6+3 tph	15 tph
Max (average) Speed	100 (29) km/h	100 (unknown) km/h	80 (23) km/h
Trip time	25 minutes	Unknown	18 minutes
Power supply	Dual-mode	25kV AC (future)	750V DC
Platform/entry height	420 mm	380 mm	380 mm

Source: TAUT, 2017

B.7 Tram-train Nantes

Table B-19: Nantes – Châteaubriant T1 parameters.

Parameter	Tram-train	Train	Tram
Line length	64 km	58 km	6 km
Stops (av. spacing)	11 (6.4 km)	9 (7 km)	2 (5 km)
Frequency	1 – 2 tph	0 + 1-2 tph	--
Max (average) Speed	100 (57) km/h	100 (60) km/h	50 (33) km/h
Trip time	67 minutes	58 minutes	9 minutes
Power supply	750V DC / 25kV AC	25kV AC	750V DC
Platform/entry height	Low-floor	Low-floor	Low-floor

Table B-20: Nantes – Clisson T2 parameters.

Parameter	Tram-train	Train
Line length	26 km	26 km
Stops (av. spacing)	8 (3.7 km)	8 (3.7 km)
Frequency	2 tph	2 + 2 tph
Max (average) Speed	100 (54) km/h	(54) km/h
Trip time	29 minutes	29 minutes
Power supply	25 kV AC	25 kV AC
Platform/entry height	Low-floor	Low-floor

B.8 RijnGouwelijn

The parameters of the RijnGouwelijn are retrieved from the pilot project that was run on the heavy rail section, between Gouda and Alphen aan den Rijn. Therefore, no tram section is included.

Table B-21: RijnGouwelijn-East parameters.

Parameter	Tram-train	Train
Line length	17.4 km	17.4 km
Stops (av. spacing)	5 (4,4 km)	5 (4.4 km)
Frequency	2 tph	2 (in peak) + 2
Max (average) speed	80 (58) km/h	100 (58) km/h
Trip time	18 minutes	18 minutes
Power supply	1500V DC	1500V DC
Platform/entry height	300mm	760 + 300 mm

B.9 Hoekse Lijn

This system is a form of train-metro and was included in this study for the technical solutions that have been used. No system parameters were investigated.

B.10 Cádiz

Table B-22 and Figure B-5 give an impression of the Cádiz tram-train line. In the line overview, it is visible that there are long interurban sections without stops, which distort the average stop spacing values. This is also a reason for the high average speed.

Table B-22: Cádiz parameters.

Parameter	Tram-train	Train	Tram
Line length	23.7 km	10.3 km	13.5 km
Stops (av. spacing)	22 (1.1 km)	5 (2 km)	17 (800m)
Frequency	4 tph	3+4 tph	--
Max (average) speed	100 (50) km/h	160 km/h	70 (ROW B) / 20 (ROW C) km/h
Trip time	28 minutes	Unknown	Unknown
Power supply	Dual-mode	3000V DC	750V DC
Platform/entry height	380 & 790 mm	760 mm	350 mm

Note: Average spacing: 2km / 800m because of long interurban stretches. Actual spacing: 1km / 400m.
Source: Novales & Conles, 2012.

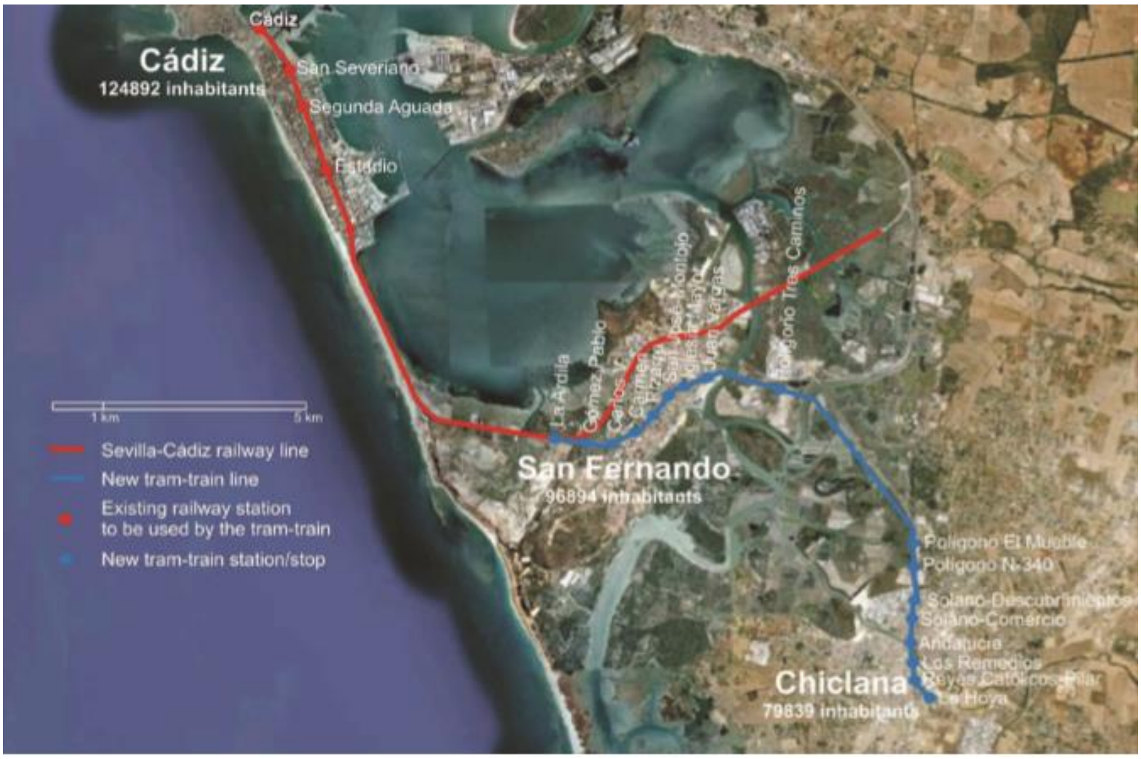


Figure B-5: Cádiz tram-train line. Novales & Conles (2012).

B.11 Cardiff

The Cardiff tram-train project consists of large parts of heavy rail operated by tram-train vehicles and only a very short section of tramway. No system parameters are included, as they would resemble too much of a pure heavy rail line.

B.12 RandstadRail

The RandstadRail is a combination of metro-train and tram-train. Table B-23 and Table B-24 give an overview of the parameters of the tram-train part (HTM Lines 3 and 4). The table is split into three sections: the shared section with the Rotterdam metro line, the ROW-A section in Zoetermeer and the tram section in The Hague. It is worth noting that the first part of the tram section in The Hague also features ROW A alignment. The network is displayed in Figure B-6. The part where the green, red and blue lines are adjacent is the shared section. The Hague is on the left.

Table B-23: RandstadRail Line 3 parameters.

Parameter	Tram-train	Shared section	ROW-A Light rail	Tram
Line length	34 km	5	18 km	11
Stops (av. spacing)	41 (800m)	5 (1km)	14 (1.3 km)	22 (500m)
Frequency	6 tph	24 tph	18 tph	27 tph
Max (average) speed	80 (30) km/h	80 (37.5) km/h	80 (42) km/h	50 (19) km/h
Trip time	68 minutes	8 minutes	26 minutes	35 minutes
Power supply	600/750V DC	750V DC	750V DC	600V DC
Platform/entry height	340 mm	300 / 900 mm	300 mm	300 mm

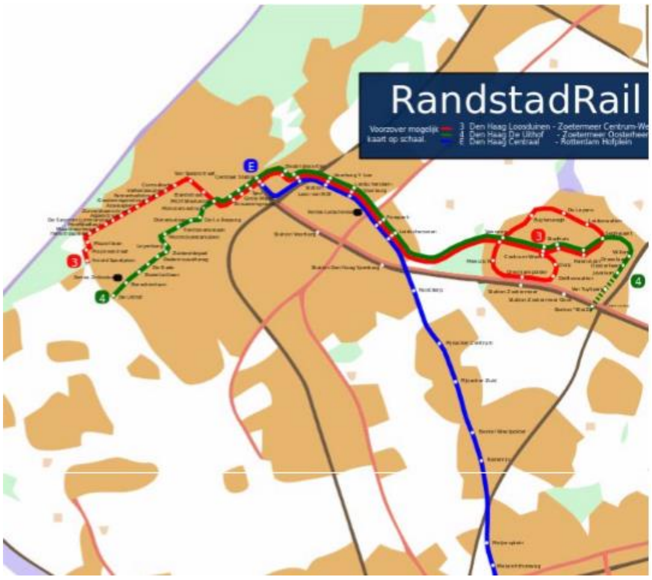


Figure B-6: RandstadRail Network. Red and green are RR3 and RR4. Blue is metro E. RandstadRail.

Table B-24: RandstadRail Line 4 parameters.

Parameter	Tram-train	Shared section	ROW-A Light rail	Tram
Line length	27 km	5 km	12 km	10 km
Stops (av. spacing)	31 (900m)	5 (1 km)	8 (1.5 km)	18 (550m)
Frequency	12 tph	24 tph	18 tph	27 tph
Max (average) speed	80 (30) km/h	80 (37.5) km/h	80 (42) km/h	50 (21) km/h
Trip time	54 minutes	8 minutes	17 minutes	29 minutes
Power supply	600/750V DC	750V DC	750V DC	600V DC
Platform/entry height	340 mm	300 / 900 mm	300 mm	300 mm

B.13 Île-de-France Tramway T4

Table B-25: Île-de-France Tramway 4 parameters.

Parameter	Tram-train
Line length	7.9 km
Stops (av. spacing)	11 (800m)
Frequency	10 tph (day) / 7 tph (evening)
Max (average) speed	70 / 50 / 30 (24) km/h
Trip time	19 minutes
Power supply	25 kV AC
Platform/entry height	Low-floor

B.14 Interpretation of the reference lines

In the following tables, the data of the systems are briefly analysed, with mean, median, minimum and maximum values. In some cases, data was not available. This is reflected in a lower number of values. A full line can exist of more than one tram- or train section. This explains why there are more analysed train sections than full lines. Similarly, the maximum number of stops for a full line

(54 stops, Karlsruhe S1) exceeds the sum of the maximum for individual tram- and train sections, as the line consists of two train sections.

Table B-26: Tram-train full line data analysis.

Parameter	Mean	Median	Minimum	Maximum	*Number of values*
Line length	32.6 km	30.6 km	7.9 km	64 km	24
Number of stops	24.8	22.5	5	54	24
Stop spacing	1.7 km	1.3 km	0.7 km	6.4 km	24
Average speed	36.6 km/h	35 km/h	23 km/h	58 km/h	24
Trip time	54.5 minutes	51.5 minutes	18 minutes	98 minutes	24
Frequency	3.1 tph	2 tph	1 tph	12 tph	24

Table B-27: Train section data analysis.

Parameter	Mean	Median	Minimum	Maximum	*Number of values*
Line length	23.3 km	18 km	4.7 km	58 km	27
Number of stops	11.1	9	2	28	27
Stop spacing	2.3 km	2 km	0.7 km	7 km	27
Average speed	44.7 km/h	44 km/h	23 km/h	60 km/h	25
Trip time	31.7 minutes	29 minutes	8 minutes	74 minutes	25
Shared frequency	4.1 tph	3 tph	2 tph	9 tph	17

Table B-28: Tram section data analysis.

Parameter	Mean	Median	Minimum	Maximum	*Number of values*
Line length	6.6 km	6 km	2.4 km	14.8 km	23
Number of stops	12.7	12	2	23	23
Stop spacing	717.4 m	450 m	300 m	5000 m	23
Average speed	19.3 km/h	18.5 km/h	11 km/h	33 km/h	22
Trip time	19.7 minutes	19.5 minutes	6 minutes	38 minutes	22
Shared frequency	21.8 tph	25.5 tph	3 tph	30 tph	22

The lengths of the reference systems are visualised in Figure B-7. The figure shows the composition of the lines, by indicating the lengths of the individual tram- and train sections. Most tram sections are less than 10 kilometres long. The exceptions are Cádiz, of which the tram part includes some interurban (regional) tram sections, Karlsruhe, of which the main tram sections traverses Karlsruhe from west to east and the RandstadRail, which has long urban sections in The Hague. Mildly supported by Figure B-8, it appears that lines with longer train sections have shorter tram sections. This can be explained from the total time required to travel the line, and the implication on reliability as described by Van Oord and Van Nes (2009).

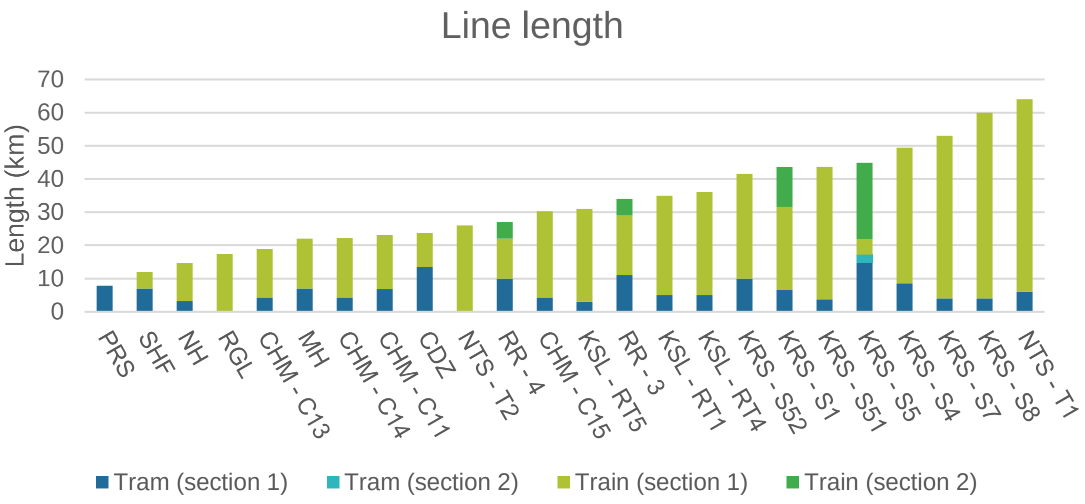


Figure B-7: Composition of line length.

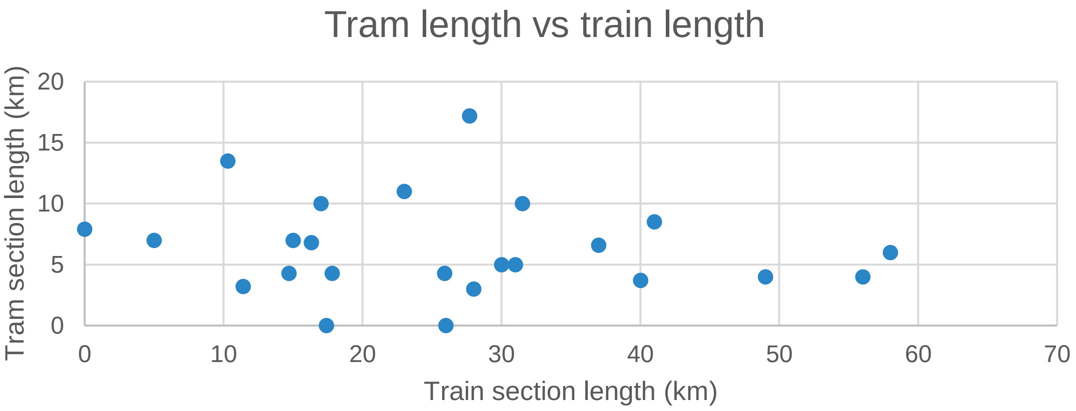


Figure B-8: Relation between length of train and tram sections.

Figure B-9 shows the length of the tram section divided by the length of the train section. A ratio of one indicates that the tram section and train section are equally long. Except for the systems of Cádiz and Sheffield (CDZ, SHF), all train sections are longer than the tram sections. This shows the regional focus of most lines, compared to the urban focus of the Cádiz and Sheffield lines.

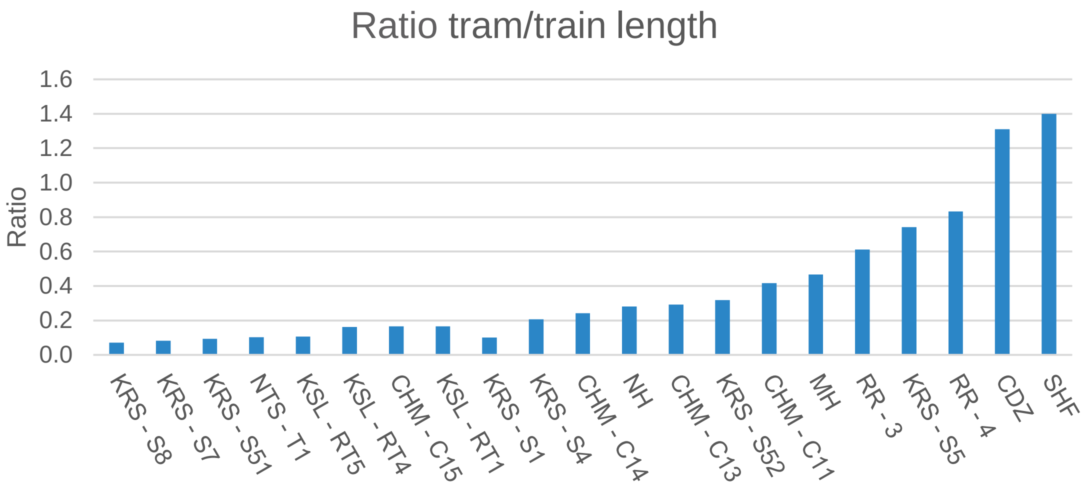


Figure B-9: Ratio between the length of tram- and train sections.

Figure B-10 shows the average stop spacing relative to the line length, for full lines, tram sections and train sections. The figure clearly shows an outlier in the tram sections; Nantes T1, which has 1 stop along 5 kilometres of tram alignment. Similarly, this line also has the largest stop spacing on the train section.

It is visible that for longer tram sections, the stop spacing increases slightly. Similarly, for longer train sections, the stop spacing increases. However, for full lines no such relation is visible. This is due to the effect of the short tram stop spacing on full lines. The larger stop spacing for longer train sections can be explained from a travel time perspective, as shown in Figure B-11. For longer lines, a higher speed (and hence longer stop spacing) is required to provide attractive travel times.

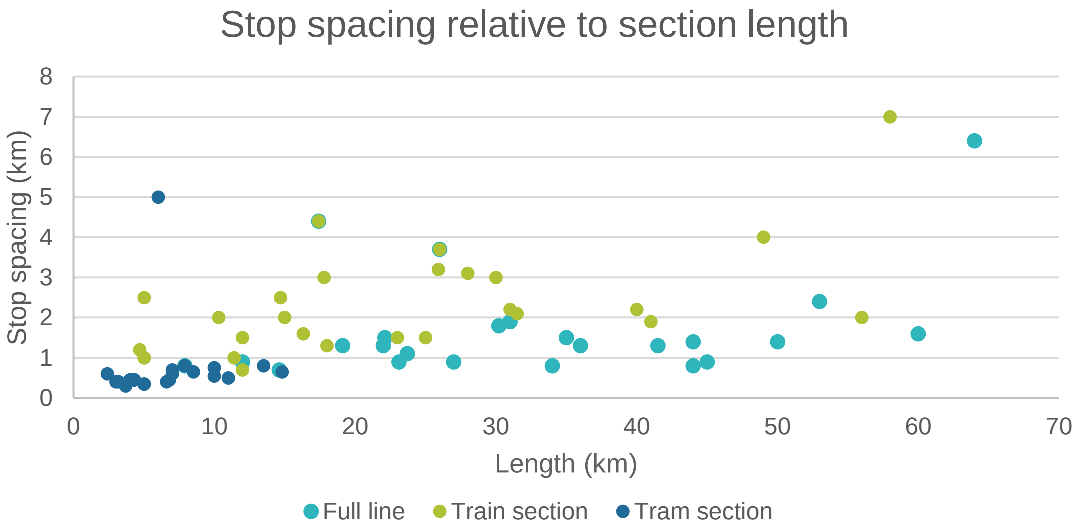


Figure B-10: Stop spacing relative to section length.

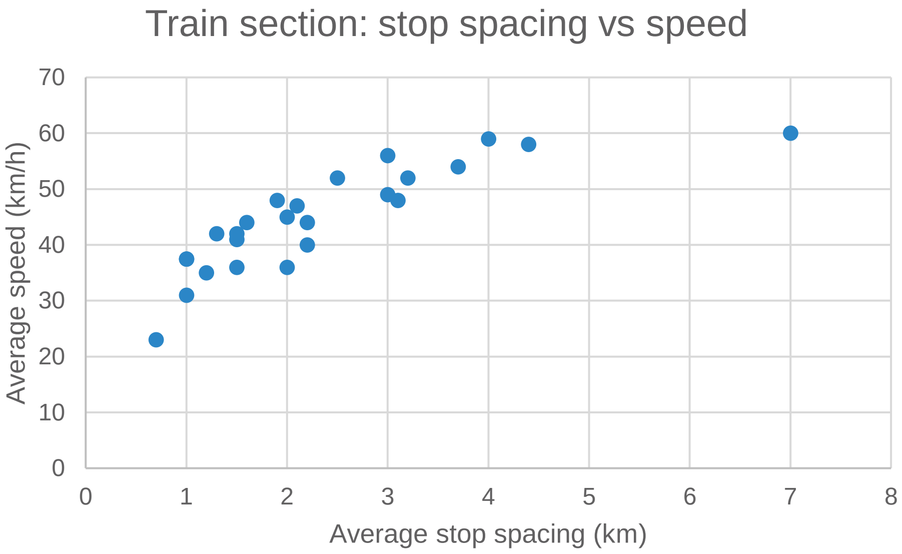


Figure B-11: Stop spacing and average speed.

C. Tram-train population analysis

Of the existing and proposed tram-train systems discussed in section 4.2, the population was analysed. This appendix briefly describes this analysis.

C.1 City and served area population figures

Table C-1 shows the populations of the cities that have been analysed. Also, the population served by the full tram-train network is given. The difference between the two figures is partly dependent on the number of lines, as more lines can serve a larger area. Figure C-1 shows the distribution of the city populations of the reference systems.

Table C-1: Population figures of analysed systems.

City	Class	City population	Population served by system
Karlsruhe	A & C	300,000	1,000,000*
Kassel	A	195,000	350,000
Chemnitz	A & C	246,000	330,000
Nordhausen	A	44,000	50,000
Mulhouse	A	112,000	150,000
Sheffield	A	550,000	650,000
Nantes	B & D	290,000	450,000
Cádiz	B	120,000	300,000
Cardiff	B	360,000	-**
RandstadRail	C	530,000 (The Hague) 650,000 (Rotterdam)	1,400,000
Paris T4	D	280,000	-***
Groningen	A	200,000	270,000
RijnGouwelijn	B	72,000 (Gouda) 121,000 (Leiden)	315,000

* Only the analysed lines, within the KVV tariff area.
** The tram-train line is a small extension to a train line, and as such less focussed at connecting the region with a destination further away from a railway station.
*** The tram-train line in Paris is a feeder line. The city population reflects the served population, as the full city population is not relevant to this specific line and would distort data analysis.

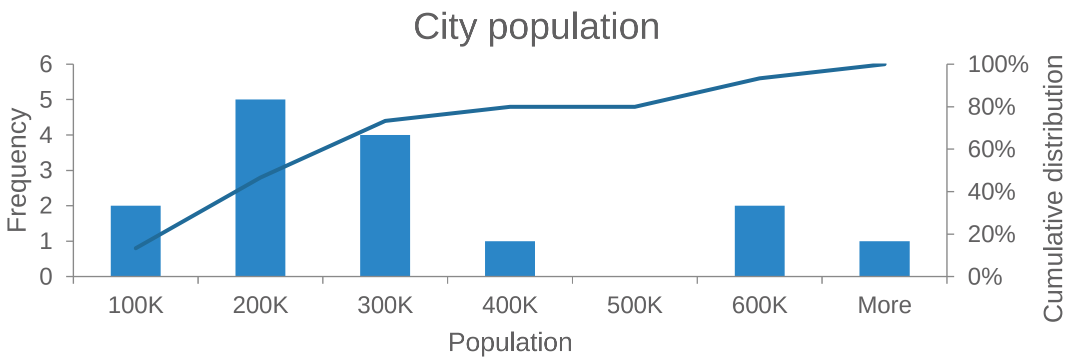


Figure C-1: Distribution of city population.

C.2 Corridor population figures

The population and corridor length of the existing and proposed systems were identified. The populations were determined by looking up the number of inhabitants for each settlement along the line. This approach is pragmatic and does not necessarily reflect the actual number of inhabitants within the catchment radius of a stop. A summary of the findings is presented in Table C-2. It was found that the average corridor serves between 40 and 50 thousand residents. However, there is a very large spread in these numbers, which is visible when the populations are displayed in a histogram (Figure C-2). An analysis of corridor length is performed in section 4.6.1.2.

Table C-2: Population figures of the analysed corridors – summary.

Parameter	Mean	Median	Minimum	Maximum	Number of values
Corridor population	59,300	47,000	6,000	202,000	31
Corridor population <100K	40,600	43,000	6,000	76,500	26
Corridor length	22.8 km	18 km	4.7 km	58 km	30
Corridor population/line-km	2300 / km	1800 / km	525 / km	7200 / km	28
City population	271,000	246,000	44,000	650,000	15
Total served population	1,130,000	350,000	50,000	8,500,000	13

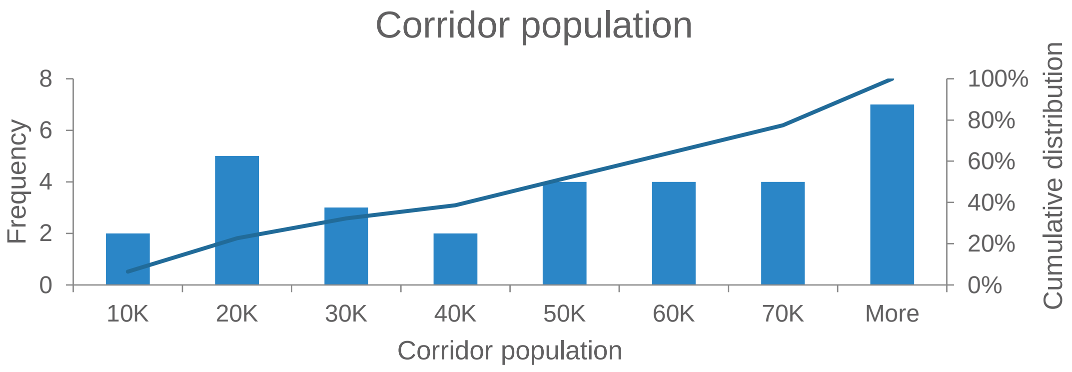


Figure C-2: Distribution of corridor population.

C.3 Corridor population per line-km

The average number of inhabitants per kilometre of line of the corridors has been determined. Only Cádiz and Sheffield-Rotherham have values of over 10,000 inhabitants per line-kilometre. Both lines only serve large cities without any smaller cores in between (San Fernando (95,000 inhabitants) & Chiclana de Frontera (82,000 inhabitants), and Rotherham (117,000 inhabitants)) and are therefore not included in the analysis. The resulting cumulative distribution is shown in Figure C-3. It was found that 90 per cent of the systems have an average population of less than 4500 inhabitants per kilometre of tram-train line. Investigation of the lines with high values reveals that these lines serve additional cities.

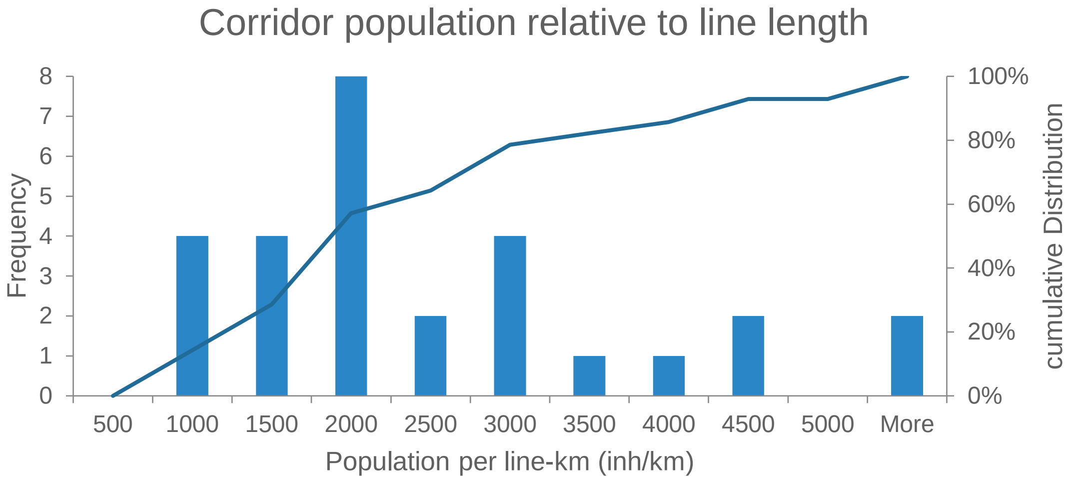


Figure C-3: Distribution of average served population per line-km (excluding Rotherham and Cádiz).

Naegeli et al. (2012) note that there is a relation between line length and serviceable population density. On shorter lines, a higher density can be served than on long lines, as the absolute number of passengers that can be transported is limited. Such a relationship was studied by plotting the total served population and line length of the analysed systems in a graph (Figure 4-8). Two apparent outliers are worth mentioning: the long lines (49 km, 4100 inh/km; 56 km, 2600 inh/km) are the Karlsruhe S7 and S8 lines, which serve multiple other cities of 30 – 50 thousand inhabitants. These lines are on the nomination to become regional railways again in the future (Kühn, 2018).

C.3.1 Derivation of class A/B-frontier

For class A & B systems, without the outliers, it appears that there is a frontier below which all systems can be found. This frontier is assumed to be linear and should include all values. Therefore, the frontier is determined by finding the function of a straight line (equation (5)) through the data points of the Gouda side of the RijnGouweLijn (Class B, approximately 17.5 km, 4400 inhabitants per kilometre) and Karlsruhe line S51 (Class A, approximately 40 km, 1725 inhabitants per kilometre).

$$Frontier = slope * line\ length + y\text{-}intercept \qquad (5)$$

The slope and y-intercept are determined by equations (6) and (7).

$$\frac{\Delta y}{\Delta x} = \frac{1725 - 4400}{40 - 17.5} = -118.9 \qquad (6)$$

$$y\text{-}intercept = 1725 - -40 * 120 = 6525 \qquad (7)$$

Inserting the values of equations (6) and (7) into equation (5) and rounding results in the approximated function of the frontier; equation (8).

$$Population\ per\ line\text{-}km < 6500 - 120 * length \qquad (8)$$

It is likely that this frontier results from the limited frequency that can be achieved when sharing tracks with heavy rail. When tracks are not shared, frequencies can be much higher and as a result, more passengers can be transported. Therefore, this frontier is not relevant for class C and D lines.

D. Tram-train checklists

D.1 Van der Bijl & Kühn (2004).

Generic features

1. State of society and social stability
2. Existing public transport culture

Institutional context

3. Powerful regional and local government
4. Existing regional and local support
5. Approach to planning process
6. Degree of integration of land use and urban planning
7. step by step implementation
8. Complementary to existing/adapted public transport network
9. Quality and capability of public transport authority, both formally and functionally, to integrate responsibility for the entire network
10. Distribution of responsibilities
11. Methods to cover construction and operating costs
12. Local/regional financial balance and sources
13. Necessary legal powers
14. Control/ownership of heavy rail infrastructure
15. Local and regional possibilities
16. Safety approach of regulatory bodies

Urban and regional characteristics

17. Distance main station to city centre (km.; walking min.)
18. Other relevant distances (km.; walking min.)
19. Availability, profile and aesthetics of centre corridor
20. (New) uses of corridor
21. Possible (positive and negative) impacts
22. Conditions historic townscape
23. Centre locations of economic activity nodes and their regional meaning
24. Economic activity nodes inside or outside TramTrain's catchment area
25. Regional meaning of central city
26. Degree of regional centre's spread

Urban and regional figures

27. Minimum and maximum sizes of city and region
28. Size of corridor's catchment area
29. Identification of the share of city/city-centre oriented flows for all user groups

Public transport characteristics

30. Competing rail modes into the city-centre

31. Other targets than the city-centre
32. Share of the total rail-bound operation in a region for TramTrain
33. Complete takeover of operation versus remaining heavy rail passenger services
34. Ratio of new-built infrastructure compared to accessible regional network
35. Tangential transport demand
36. Street-running extensions in sub-urban centres useful/feasible
37. Additional catchment by using existing tangential infrastructure
38. Existing/achievable interchange quality between railway and urban system
39. Comparison of travel times

Technical issues

40. Existing tramway's technical parameters
41. Metro operation (tunnel)
42. Easy versus difficult (cheap versus expensive) linking of tramway and railway
43. Electrified/non-electrified regional railway infrastructure
44. Track-sharing versus conversion
45. Existing (urban) freight railway infrastructure
46. Platform heights of (regional) railway routes
47. Full accessibility

Costs and cost comparisons

48. Comparison of modes
49. Political decision vs evaluation
50. "Tenderability" of TramTrain-scheme

D.2 Naegeli, Weidmann and Nash (2012).

Characteristics of cities

1. Size of the city
2. Regional metropolis
3. Existence of a suitable tram corridor
4. Conversion of the corridor (monument conversation?) (Type B only)
5. City too small for tram network - bus used to capacity (Type B only)
6. Existence of a main centre of activity
7. Further smaller centres of activity along the line
8. Distance between railway station and centre 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 (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) (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, organisational 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 centre)
33. Existing development plans

34. Rough comparisons with possible alternatives: costs and benefits
35. [Other application area, e.g. tangential connections (tram-train Paris)]

Basic conditions

36. Capacity and capability (verification)

E. Suitability scan

E.1 Expert judgement on criteria

In this appendix, the weights for the weighted-sum multi-criteria analysis of the suitability scan are determined. First, the input of five experts is discussed. Secondly, the judgements of the five are used to set the weights for the designed model.

E.1.1 Expert judgement

Five experts from light rail practice and research have been asked to give their opinion on the weight of the criteria used in the suitability model. For each criterion, they were asked to rate the relative importance on a scale ranging from 1 (least important) to 5 (most important). Table E-1 lists the scores. The data is anonymised.

Table E-1: Expert judgement on the weights of the suitability scan criteria.

Criterion	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
I. Population and regional structure					
1. Density of regional settlements	4	4	4	2 [4.1]	5
2. Presence of multiple corridors	2	3	1	3	2
II. Relation city-region					
3. Relation between city and region	4	5	4	4	3
4. Served attraction centres	5	4	5	5	4
5. Location of main railway station	3	3	3	5	2
III. Public transport corridors					
6. Easiness of connection	3	3	2	3	5
7. Tram width	2	4	1 [3.1]	1	1
8. Tram length	1	2	1	2	2
9. Service quality of tram corridor	3 [1.1]	3	3	3	4
10. Shared frequency on tram network	1 [1.2]	3	4 [3.2]	3	1
11. Main station layout	2	1	2	2	2
12. Tram-train vehicle design speed	4	2	2	3	2
IV. Access and egress					
13. Cycling	3	2	3	1	2
14. Public transport	2	3	3	3	4
15. Park & Ride	2	1	1	3	4
Total number of points distributed	*41*	*43*	*39*	*43*	*43*

1.1: This aspect becomes more important when the shared frequency on the respective sections increases.
1.2: In itself this is of small importance, the boundary conditions already capture the essence of this criterion.
3.1: This expert regards the width more as a technical issue
3.2: This expert regards this criterion as very important when frequencies are high, but at low frequencies this criterion is unimportant.
4.1: This expert regards this criterion as important for all public transport, and not specifically for tram-train.

E.1.2 Determining weights for the designed model.

The experts' opinions were analysed. The difference between the highest and lowest value (Δ-max) was determined. For the criteria with a large difference, it was found that on most occasions three experts gave similar weights, one scored the criterion lower and one higher. Therefore, it was decided to determine the final weight (w_j) by eliminating the highest and lowest value and taking the mean value of the remaining three (9). This value was rounded to the nearest integer.

$$w_j = \frac{\sum w_{j,e} - min(w_{j,e}) - max(w_{j,e})}{3} \qquad (9)$$

Table E-2: Analysis of expert judgement and resulting weight w_j.

Criterion	Δ-max	min	max	w_j
I. Population and regional structure				
1. Density of regional settlements	3	2	5	**4**
2. Presence of multiple corridors	2	1	3	**2**
II. Relation city-region				
3. Relation between city and region	2	3	5	**4**
4. Served attraction centres	1	4	5	**5**
5. Location of main railway station	3	2	5	**3**
III. Public transport corridors				
6. Easiness of connection	3	2	5	**3**
7. Tram width	3	1	4	**1**
8. Tram length	1	1	2	**2**
9. Service quality of tram corridor	1	3	4	**3**
10. Shared frequency on tram network	3	1	4	**2**
11. Tram-train vehicle design speed	1	1	2	**2**
12. Main station layout	2	2	4	**2**
IV. Access and egress				
13. Cycling	2	1	3	**2**
14. Public transport	2	2	4	**3**
15. Park & Ride	3	1	4	**2**

E.1.3 Experts (alphabetically)

- Bogdan Godziejewski & Ricks Schalk; senior rail manager respectively consultant rail transportation, Mott MacDonald.
- Janneke Tax; consultant rail transportation, Mott MacDonald.
- Martijn Donders; practice leader LRT, Mott MacDonald.
- Niels van Oort; assistant professor Public Transport, Delft University of Technology.
- Rob van der Bijl; independent consultant light rail.

E.2 Suitability scan results

Table E-3 shows the outcome of existing systems when tested in the suitability scan. The end score percentage is the result provided by the suitability scan.

Table E-3: Suitability scan results.

Line	Class	Score (I)	Score (II)	Score (III)	Score (IV)	End score
Karlsruhe S1-S	C	68%	70%	60%	52%	64%
Karlsruhe S1-N	C	89%	75%	59%	39%	64%
Karlsruhe S4	C	79%	85%	73%	37%	72%
Karlsruhe S5-W	A	89%	85%	59%	39%	67%
Karlsruhe S5-E	A	68%	87%	63%	69%	73%
Karlsruhe S5	A	89%	94%	53%	54%	71%
Karlsruhe S51	A	79%	72%	74%	60%	72%
Karlsruhe S52	A	79%	75%	67%	55%	69%
Karlsruhe S7	A	89%	75%	65%	55%	71%
Karlsruhe S8	A	47%	75%	65%	54%	64%
Kassel RT1	A	68%	75%	59%	70%	67%
Kassel RT4	A	68%	75%	63%	68%	68%
Kassel RT5	A	68%	75%	80%	70%	75%
Chemnitz C11	C	47%	72%	71%	31%	61%
Chemnitz C13	A	68%	75%	77%	53%	71%
Chemnitz C14	A	68%	75%	81%	53%	72%
Chemnitz C15	A	79%	70%	77%	53%	72%
Nordhausen	A	21%	73%	0% 64%	9%	0% 51%*
Mulhouse	A	53%	65%	65%	57%	63%;
Sheffield	A	74%	66%	59%	37%	59%
Nantes T1	B	68%	69%	0%	51%	0%**
Nantes T2	D	100%	74%	0%	72%	0%**
RijnGouwelijn	B	42%	72%	49%	88%	62%
Cádiz	B					Scan could not be applied***
Saarbrucken S	B	68%	61%	62%	59%	62%
Saarbrucken N	B	68%	66%	62%	59%	64%

* The boundary condition 7.29 of Nordhausen is to be interpreted differently, as the implementation is between metre-gauge systems.
** The boundary condition of criterion 7 was not met. Therefore, tram-train is not a realistic solution.
*** It was not possible to determine several input values for the area around Cádiz. A detailed explanation is given in section 5.3.2.

F. Technical solution library

This appendix provides a library of experienced technical issues with interfaces between the components of tram and train systems. For several issues, there are multiple solutions, which are assessed by using the method described in section 5.4.2. The assessment criteria are also provided in Table F-1. Other issues are listed in the library as general points that require attention. This library with issues and solutions can be used as a reference document for further feasibility studies of tram-train solutions.

Table F-1: Assessment criteria for technical solutions.

	○	●	●●	●●●
Cost *Reference: not implementing the solution.*	Not more expensive than the reference situation.	A small increase in cost compared to the reference. E.g. small modifications to a limited number of vehicles or a small section of infrastructure.	A large increase in cost compared to the reference. E.g. both rolling stock and infrastructure need to be modified.	A very large increase in cost compared to the reference. E.g. very extensive infrastructural modifications required.
Operations (planning, capacity/speed, procedures, human factors) *Reference: existing operations.*	No impact on operations.	Small impact on operations.	Large impact on operations.	*Not applicable*
Rolling stock (existing) *Reference: no modifications to existing rolling stock (train / tram) required.*	No modifications to existing rolling stock need to be made.	A small modification (e.g. retrofit) should be made to a limited number of vehicles.	A small modification should be made to a large/complete fleet of vehicles, or a large modification should be made to a limited number of vehicles.	A large modification should be made to a large/complete fleet of vehicles.
Rolling stock (new) *Reference: a regular urban tram.*	A reference vehicle can be used without modification.	A small modification should be made to a reference vehicle.	A large modification should be made to a reference vehicle.	*Not applicable*
Rail infrastructure *Reference: no modifications to infrastructure.*	No modifications to the rail infrastructure need to be made.	Small modifications should be made to the rail infrastructure.	Large modifications should be made to a small part of the rail infrastructure.	A large modification should be made to the full corridor (e.g. new signalling system).
Stations *Reference: no modifications to infrastructure.*	No modifications to the stations required.	Small modifications to stations required (e.g. remodelling of a platform).	Large changes to stations required (e.g. layout changes, new platforms).	*Not applicable*

F.1 Rolling stock

When there are shared operations (Class A and B and in train-tram), an interface exists between the various vehicles that use the same tracks. This interface is mostly physical, in the event of a collision. Railway signalling systems are designed to prevent setting conflicting routes for trains. Although signalling systems are designed to be fail-safe, collisions still occur due to human error. The weight difference between trains and trams makes the lighter tram vehicles vulnerable to large deformations (due to their limited momentum), which is dangerous to passengers.

Passenger safety in the event of a collision depends on active and passive safety measures. Passive measures are incorporated in the structural design of vehicles and minimise the damage after a collision has taken place. Active safety measures are meant to reduce the chance of a collision, or at least reduce the impact velocity as much as possible. Both passive and active safety are discussed in more detail in the next paragraphs.

F.1.1 Passive safety

F.1.1.1 Crashworthiness and structural strength regulations

There are European standards that prescribe requirements on longitudinal rigidity (DIN EN 12663) and crashworthiness (DIN EN 15227). The application of these standards for tram-train operations varies per country. In Germany, Article 2 of the EBO (Eisenbahn-Bau- und Betriebsordnung) states that vehicles must be designed to comply with safety regulations by applying recognised technical rules. Deviation from the regulations is allowed if the level of safety can be demonstrated to be at least equally high. See Table F-2. In other countries, such as France and the Netherlands a more case-by-case approach is used (Kühn, 2007).

Table F-2: Application of EN standards in Germany to comply with EBO regulation (2014).

Operation	Longitudinal rigidity	Crashworthiness
Heavy rail	1500 kN (P-I / P-II)	C-I
Class C & D	400 kN (P-IV)	C-III
Class A & B	800 kN (P-III)	C-III

Source: Boenke & Girnau (2014).

Coupler height and cab design

In passenger trains, the coupler plays a small role in absorption of impact energy. However, low-floor trams have couplers at a lower height than trains, which eliminates the effect of this absorption mechanism. Moreover, the cabs of trams are lower, to provide sufficient forward view in urban environments. As a result, the cabin of tram-train vehicles should be designed such that this forward view is fully compliant to regulations, while structural rigidity is provided at the height of couplers of heavy rail vehicles (Stadler, 2018).

F.1.1.2 Time separation

If the tram-train shares its tracks with a few freight trains per day, or even less, it can be worthwhile researching the possibility of time separation. During the day, tram-trains operate on the line, while at night, freight trains use the tracks. This eliminates the risk of vehicle-vehicle collisions and allows higher tram-train frequencies. However, night-time operations of freight trains can cause disturbances to residents along the tracks. When the shared section is relatively short, it can be possible to fit a single freight train in the timetable and cease operation of tram-train until the freight train has left the tracks. This solution is used on the Hoekse Lijn in Rotterdam (Kats, 2018).

Table F-3: Assessment of passive safety solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Construct tram-train vehicles to comply to P-III & C-III standards	●	○	Existing: ○ New: ●●	○
Use time separation to prevent train-train collisions	○	●●	○	○

F.1.2 Active safety

Active safety of light rail vehicles is improved over heavy rail vehicles. They are lighter than trains, which allows them to achieve better braking performance (minimal deceleration of 2.8m/s^2, compared to 1.5m/s^2). As a result, it is easier to avoid collisions with other rail vehicles (Boenke & Girnau, 2014).

F.1.3 Pressure effects of crossing trains

At high speeds, trains move large volumes of air around the vehicle, creating pressure effects between two crossing vehicles. These pressure changes can affect doors, windows and passenger comfort. In the Cádiz case, simulations showed that the initial door design could be unsafe when crossing with the most unfavourable train running at 160 km/h. Therefore, the doors had to be redesigned (Novales & Conles, 2012). For similar reasons, in Germany, the maximum speed of trains operating on shared sections is limited to 160 km/h, and 120 km/h in tunnels (LNT Richtlinien).

Table F-4: Assessment of pressure effect solution.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Limit speed of crossing trains	○	●	○	○

F.1.4 Towing facilities

As mentioned, the height of couplers of tram-train vehicles and trains is likely not the same. Therefore, provisions should be made to ensure stalled or broken tram-train vehicles at the heavy rail tracks can be rescued by other trains or rescue locos (Novales & Conles, 2012).

F.1.5 EMC

The different technology and higher currents used in trains result in stronger electromagnetic emissions than trams. Tram-trains on electrified heavy rail lines are susceptible to these stronger emissions and should be thoroughly tested on their electromagnetic compatibility (Godziejewski, 2018).

F.2 Rolling stock & Infrastructure

Heavy rail tracks are designed to be used exclusively by trains, while tramways are built in an urban environment, where space is often limited. In situations where trams operate together with road traffic, tram vehicle dimensions are legally limited (BOStrab) to match those of road traffic (trams are up to 2.65m wide, buses up to 2.60 (Table 3-4)). However, when the relatively small vehicles operate on the main lines, they should be able to interact with the heavy rail infrastructure safely.

F.2.1 Passive safety: level crossings

Although the improved braking characteristics of light rail vehicles can reduce the impact speed of a collision, the lighter weight increases the risk of derailments after collisions on level crossings, especially when heavy road vehicles are involved. In the RijnGouwelijn trial, this risk was analysed, and three solutions were presented (Arcadis, 2003; 2004).

- To prevent escalation of a derailment, additional guiding rails can be placed in the centre of the tracks. These ensure the vehicle will stay within the track alignment and prevent crashes with other infrastructure such as overpasses (Arcadis, 2004).

- Reducing the train speed on level crossings improves the probability of a vehicle coming to a stop before a level crossing, thereby preventing a collision. If a collision does occur, the impact speed will be low, with a very low risk of injuries or fatalities (Arcadis, 2003). However, reduced speed can decrease the stability of a timetable (PZH, 2006).
- Banning trucks and other heavy traffic from level crossings reduces the risk of a potentially fatal collision, but this requires alternatives for such vehicles. If there are no alternative possibilities for trucks to cross the tracks, this solution will likely not be acceptable (Arcadis, 2003).

Table F-5: Assessment of level crossing solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Construct guiding at level crossings to prevent escalation of derailment	●	○	○	Rail: ● Stations ○
Reduce maximum speed near level crossings	○	●	○	○
Ban heavy road vehicles from level crossings	○	○ *	○	○

* Banning certain road vehicles from level crossings does not influence operations on the railway but can have a large implication for the level crossing users.

F.2.2 Active safety

To be operated safely on heavy railways, tram-train vehicles should be equipped with a form of automatic train protection (ATP). Typically, this will be the same system as used by regular trains. Although active safety of tram-train vehicles is higher than regular trains because of their braking characteristics (F.1.2), this may not be enough to compensate for the reduced passive safety. The active safety on railways can be increased by reducing the chances of trains passing signals at danger (SPADs) (PZH, 2006).

In the Netherlands, for the RijnGouwelijn trial (PZH, 2006), an increased level of active safety was achieved by installing ATB-NG at the relevant section. ATB-NG has braking curve supervision (contrary to ATB-EG, the principal Dutch train protection system), which reduces the risk of a signal passed at danger (SPAD). In turn, this reduces the risk of a tram-train vehicle from entering a section reserved for a train. Systems with braking curve supervision can contribute to travel time savings, which is discussed in F.6.2.

On the other hand, developing specific on-board ETCS equipment for a small number of vehicles can be very expensive (Godziejewski, 2018). When only a short corridor with ETCS is concerned, it can be financially more attractive to create an overlay for tram-train with less functionality.

The impact on existing infrastructure and rolling stock depends on whether systems will be replaced, or a dual-signalling system is implemented. In the second case, existing rolling stock need not be modified.

Table F-6: Assessment of active safety (signalling system) solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Replace ATP system to include braking curve supervision for all trains	●●● *	●● *	Existing: ●● - ●●● New: ●	Rail: ●●● Stations: ○

Solution	Cost	Operations	Rolling Stock	Infrastructure
Install overlay system or dual-signalling with braking curve supervision only for tram-train	●●	●	Existing: ○ New: ●	Rail: ●●● Stations: ○

* Cost of replacing a full ATP system on a corridor can be extremely large, as is currently experienced in Europe with the transition to ERTMS. However, the benefits of a new signalling system range beyond safety and can include improved track capacity and reduced travel times.

F.2.3 Rolling stock – platform interface

F.2.3.1 Floor height and boarding height

In section 2.2.2.3 it was found that providing level boarding can shorter travel times. Besides, level boarding is important for PRM access. However, there can be differences between the platform height of tram and train systems. Low-floor tram systems have platforms around 33 cm above the top of rails (a.t.r.), while train platform height is specified by the infrastructure TSI and should be 55 or 76 cm a.t.r. (ERA, 2015).

For full accessibility, either all platforms along the tram-train route should have the same height, or the tram-train should have two entrance heights with provisions inside the vehicle to allow movements between the different floor heights.

- It is possible to create separate platforms or partly reduce platform height at stations, to allow level boarding at low-floor tram-trains. For this, one should also refer to the platform gap and possible loading gauges (PZH, 2006).
- Similarly, the tram platforms can be modified to allow middle-floor or high-floor tram-trains. However, this increases the required space for tram stops and can be difficult to fit in an urban environment. A partial solution exists, in which a short section of the tram platform is raised to vehicle floor height (Figure F-1). This requires less space but can complicate the use of double traction. If two vehicles are combined outside the city, and operated as double traction within the city, only the front vehicle offers level boarding (Kühn, 2018).
- In several systems, vehicles with two entrance heights are in use. On low-floor platforms, all doors can be used, although the high doors require steps. On high platforms, only the high doors are usable, which reduces boarding- and alighting speed. Inside the vehicle, a ramp can be constructed (Chemnitz vehicles) or a small wheelchair lift can be built (Cádiz vehicles). The ramp should comply with the PRM TSI.

Figure F-1: Raised platform for two doors, Karlsruhe.

Table F-7: Assessment of boarding height difference solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Two–height platforms*	●	○	○	Rail: ○ Stations: ● - ●●
Two-level vehicles – ramps	●	●	Existing: ○ New: ●●	○
Two-level vehicles – lift	●	●	Existing: ○ New: ●●	○
No guaranteed level access	○	●●	○	○

* Also refer to F.2.3.2 and F.2.8.

F.2.3.2 Platform gap

The distance between the platform and vehicle entrance should be sufficiently small, to enable easy boarding and prevent unsafe situations. Tram-train vehicles are narrower than regular trains (2.65m and up to 3.15m, respectively), so provisions should be made to reduce the gap between the platform and the vehicle. Low-floor vehicles are slightly advantaged by the structure gauge of heavy railways, which makes it possible to reduce the distance between the tracks and low platforms. This is discussed in F.2.8.

- In Kassel, a form of gauntlet track was used to bring the narrow vehicles close to platforms (Figure 4-5), while in the Hoekse Lijn, gauntlet track is used to divert the freight trains away from the platforms (Kats, 2018). In such a case, it should be ensured that the diversion does not interfere with the loading gauge of the crossing track. Gauntlet tracks are a complex technical solution, which requires points, and likely results in modifications to signalling system and interlocking. If this issue exists at a single station, gauntlet track can be a feasible solution, but if it is required at several stations, the cost will increase rapidly.
- Much like the gauntlet track solution, it is also possible to construct an additional track and platform for tram-train services, in which the platform height and distance to the vehicle are adjusted specifically for the tram-train. Separate tram-train tracks enable overtaking movements, which is beneficial for the track capacity. However, the construction of additional tracks is expensive and requires more space at each station. Moreover, the location of the new platform might eliminate the possibility of cross-platform interchanges, which requires longer transfer times.
- Using retractable steps in vehicles temporarily increase the width of vehicles, which reduces the platform gap. Retractable steps are a common feature in both light rail and heavy rail systems. However, the maximum gap that can be covered by steps is limited (Kühn, 2018).
- Most vehicles have steps that extend when the doors are opened and retract with the departure process, but in Amsterdam on metro-tram line 51, semi-fixed steps are used. When a vehicle runs on the tram alignment, the steps are retracted. When the vehicle enters the metro alignment, the steps are unfolded. With the extended steps, the vehicle still fits within the loading gauge. The advantage of these semi-fixed steps is the greatly reduced number of movements, which causes less wear.

Table F-8: Assessment of platform gap solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Gauntlet track	●●	○	○	Rail: ●● Stations: ○
Separated tracks & platforms	●●	○ - ●	○	Rail: ●● Stations: ●●

Solution	Cost	Operations	Rolling Stock	Infrastructure
Retractable steps – per station	●	○	Existing: ○ New: ●●	○
Retractable steps – semi-fixed	●	○	Existing: ○ New: ●	○

F.2.4 Traction supply

Most trams are powered by electrical engines, from 600V DC or 750V DC overhead lines. However, heavy rail lines are powered by diesel engines, or higher overhead line voltages. Common voltages are 1500 and 3000V DC, and 25kV AC. In some German-speaking countries, as well as some Scandinavian countries, 15kV AC, 16 2/3 Hz is used. Trams designed for 750V DC can be operated on 600V networks without modifications, but not on higher-voltage heavy railway lines.

F.2.4.1 Bi-current vehicles

To operate trams on electrified heavy rail lines, bi-current vehicles are used. The vehicles are equipped with down chopping or transforming equipment that reduces the heavy rail overhead line voltages to the required voltage for the engines. When using bi-current vehicles, attention should be paid to the increased weight of the additional electrical equipment (Boenke & Girnau, 2014). See also section F.2.5.

F.2.4.2 Unelectrified main lines

Many heavy railway lines are not electrified. Diesel traction is very common and can be a lot cheaper than the construction and maintenance of overhead line equipment. However, when former unelectrified lines become part of a tram-train network, traction for the electric engines should be supplied.

- Bi-mode vehicles (diesel / hydrogen)

  When a tram-train service is to be operated on lines that will not or cannot be electrified, it is possible to provide the required tractive power by diesel engines on board of the tram-train vehicle. In Kassel and Nordhausen (both Germany), services are provided by diesel/electric bi-mode vehicles (NVV, 2006). However, diesel engines emit noise and polluting gases. Moreover, diesel-powered vehicles require stops for refuelling. The Kassel RegioCitadis is equipped with a fuel tank of 300 litres, which allows for 900 kilometres of diesel-powered operation (NVV, n.d.). The vehicles are prepared for pressure-filling, to minimise the time needed for refuelling (NVV, 2006).

  Trials are planned with hydrogen powered trains and trams, instead of diesel power (Baker, 2018). As technology improves and hydrogen proves to be a reliable source of tractive energy, it might be possible to equip tram-train vehicles with hydrogen fuel cells. This way, the downside of diesel engines (noise and gas emission) is removed. Still, refuelling stops will be necessary.

- Electrification – 600/750V

  For the Hoekse Lijn (NL), an old railway stretch was converted to a metro-train line, with an overhead line voltage of 750V, like the rest of the surface metro network. Still, a few freight trains use the line, which must be powered by diesel locomotives (or electric locomotives with diesel last-mile capabilities). Such modifications can only be done after all involved parties have agreed (Kats, 2018). Therefore, electrification at tram system voltage is most suitable for class C / D systems.

- Electrification – main line voltage

  Another possibility is to electrify the main line at the voltage of the rest of the network. This also allows national train operators to operate electric trains at such lines. If this solution is chosen, the tram-train vehicles must be bi-current, as discussed in section F.2.4.1.
- Battery operation

  In some cities, trams traverse short sections on battery power. If the main line section is short enough to be operated on battery power, the tram-train vehicles can be equipped with batteries to travel the distance.

  There are also instances in which main lines cannot be electrified everywhere, due to low height clearances in old structures. If the unelectrified stretches are too long to be overcome without traction, batteries provide an adequate solution. Therefore, in Cardiff, dual-mode battery / 25kV AC vehicles will be used (Briggs, 2018).

  When battery-powered tram vehicles are used, additional attention should be paid to the life-cycle costs, as batteries have a limited lifespan (Donders, 2018).

F.2.4.3 Unelectrified tramways

There can be tramways where no overhead lines are present, for example to preserve old townscapes, or because there are height restrictions.

A tram-train service can be created by extending a heavy railway onto a street alignment, but without providing overhead lines. An example is Cardiff, where a line is extended by 400 metres as a tramway – with running on sight, but no overhead power supply (Briggs, 2018).

It is possible to equip trams with batteries or supercapacitors for short distances without power supply. In the future, hydrogen might be a feasible power source as well. See section F.2.4.2.

Table F-9: Assessment of traction power supply solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Bi-current tram-train vehicles	●	○	Existing: ○ New: ●●	○
Bi-mode vehicles	●	●	Existing: ○ New: ●●	○
Electrify train section at 600/750V	●● - ●●●	●	○	Rail: ●●● Stations: ○
Electrify train section at main line voltage	●● - ●●●	●●	Existing: ○ New: ●●	Rail: ●●● Stations: ○
Battery operated trams	●	○	Existing: ○ New: ●	Rail: ●● Stations: ●

F.2.5 Axle loads

Trams are lighter than trains. Maximum axle loads at heavy railways will therefore not be an issue. However, tram-train vehicles can be heavier than regular trams, as a result of stronger construction to withstand crashworthiness norms and additional power equipment. Existing tram tracks must be able to carry these heavier vehicles. Especially in cities with old infrastructure, such as the bridges in Amsterdam, maximum axle loads can restrict the type of vehicles that can be operated. The standardised tram-train vehicle, as proposed in Streeter (2018) is designed with a foreseen maximum axle load of 10.7 – 11.5 tons, which is similar to typical tram design characteristics. Some weight savings can be obtained by omitting passenger air conditioning equipment, although this reduces passenger comfort.

F.2.6 Wheel-rail interface

The main interface between rolling stock and interface is the wheel-rail interface. However, there are large differences between tram and train rail profiles and wheel profiles. Tramways often use grooved rails, which are never used on heavy railways. Moreover, heavy rail tracks generally have an inclination of 1:20, while most tram tracks are either vertical or have an inclination of 1:40 (Allen & Bevan, 2008). Furthermore, trams often have wheels with a smaller diameter than trains. Crosbee et al. (2016) identified five challenges in the interface between wheels and rails, while assessing a suitable wheel profile for the Sheffield tram-train pilot.

1. Geometric dimensions of the groove of the tramway's grooved rails.
2. Back-to-back spacing between the wheels.
3. Different rail profiles.
4. Different design of switches and crossings.
5. Flange tip running in switches on tram tracks.

There may be situations in which not all challenges are relevant. Basically, three kinds of solutions to the wheel-rail interface exist (Haering, 2018).

- When no tram network is present, a rail profile suitable for train wheels can be used as tram tracks. In Saarbrucken and Cádiz, wide grooved rails are used in street alignments (Haering, 2018; Novales & Conles, 2012). These grooves permit the usage of wheel profiles with wider flanges than typically found on trams. However, wider grooves pose a greater danger to cyclists. This solution can also be applied to existing networks, although it will likely result in high costs. Furthermore, it should be checked whether the rails can still safely be used by other trams.
- A specific wheel profile can be designed, which has adequate running characteristics on both tram and train tracks. The wheel profile features a tram wheel flange, with thickened flangeback for proper interaction with check rails on points. This solution was used in Sheffield (Crosbee et al., 2016) and in Karlsruhe (Haering, 2018).
- The main issue of tram wheels on heavy rail tracks is experienced at points (PZH, 2006; Crosbee et al., 2016; Vreeswijk, 2018). It is possible to modify points in such a way that tram wheels with a smaller diameter and flange can safely cross the points. To achieve this, points can be equipped with moving noses. In the RijnGouwelijn trial, there were concerns about the safety of small wheels on double slip points. To overcome this, slightly altered frogs were implemented (PZH, 2006).

Table F-10: Assessment of wheel-rail interface solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Build new tram tracks which allow heavy rail wheel profiles	○	○	○	○
Modify tram tracks to allow heavy rail wheel profiles	●●	○	Existing: ●● New: ○	Rail: ●●● Stations: ○
Modify wheel profile to operate on both types of track	●	○	Existing: ○ New: ●	○
Modify heavy rail switches to be operated by tram wheel profiles	●	○	○	Rail: ● Stations: ○

F.2.7 Existing track alignment and vehicle limitations

For the RandstadRail, a connection between the existing The Hague tram network and heavy rail station was made. The branch was located close to an existing curve (V_{design} = 70 km/h, R = 200m, cant = 150 mm). The build-up of the cant exceeded what was allowed for the new rolling stock, as the low-floor tram-trains are stiffer. Especially at low speeds, this combination results in increased risk of derailment. Vehicles entering the branch are limited to a speed of 25 km/h, and a signal was placed near the curve, often holding vehicles. A vehicle accelerating from standstill derailed in the curve (OvV, 2008). This situation revealed two problems: the track alignment was not suitable for the tram-train vehicles, and the position of the connection made it impossible to traverse a nearby curve at track design speed.

It should be ensured that track alignment and vehicles are fully compliant. When temporarily restrictions are relieved, the environment (e.g. nearby speed limitations or signals) should be considered. The *safety case* should include an assessment of actual track conditions relative to vehicle specifications (OvV, 2008).

When designing a new connection, it should be ensured that the connection can be constructed such that nearby track sections principally can be traversed at their design speed.

F.2.8 Loading gauge and structure gauge

The loading gauge of trains and trams differ. The most common UIC loading gauges slope inwards towards the rails below a height of 380mm a.t.r. Although tram rolling stock is generally narrower than heavy rail rolling stock, the shape of trams tends to be more boxed. The width of trams is more constant towards the bottom of the vehicle. Therefore, it is possible that the loading gauge of trams reaches outside the structure gauge of heavy railways, as visible in Figure F-2 (PZH, 2006).

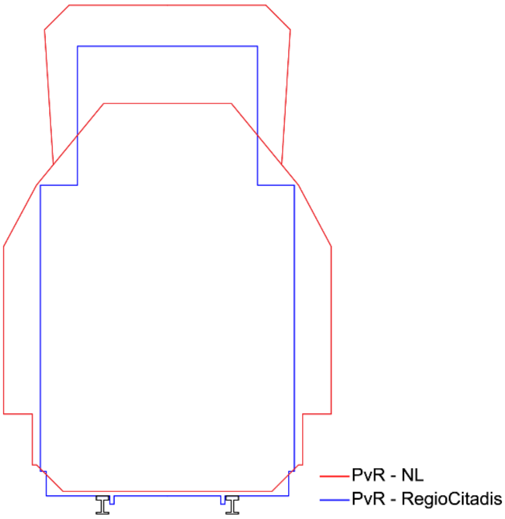


Figure F-2: Difference between structure gauge of Dutch Railways (red) and the RegioCitadis tram-train vehicle (blue).

- The heavy rail tracks should be checked for compliance to the tram-train vehicle loading gauge. It is possible that equipment should be moved. If equipment of the ATP system (e.g. beacons) is within the loading gauge of the vehicles, this should be lowered or moved. However, it should be ensured that this does not disrupt the functioning of the equipment. An example of such systems is the Crocodile (Figure F-3), used in Belgium, Luxembourg and France.

Figure F-3: Crocodile ATP contact, clearly reaching above the top of rails. Marc Ryckaert.

- Alternatively, the vehicle design can be altered to make space for the equipment or objects. In Mulhouse, the bottom of the tram-train has an inwards-rounded shape, to comply to the structure gauge. As a result, retractable steps were required to ensure a gap-free access at tram stops.

Table F-11: Assessment of loading gauge solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Check for compliance to tram-train loading gauge, move (non-safety critical) trackside objects	○ - ●	○	○	Rail: ○ - ● Stations: ○ - ●
Modify tram-train vehicle design	●	○	Existing: ○ New: ●●	○
Move (safety-critical) trackside objects	● - ●●	○	Existing: ○ - ● New: ○	● - ●●

F.2.9 Train detection system

Almost all heavy rail tracks are equipped with train detection systems (except for unprotected lines and in the future for ETCS Level 3). The train detection system is connected to the signalling system and detects whether track blocks are occupied or free. The train detection system is also used for activation of level crossings. Therefore, for safe operations, it is of prime importance that each rail vehicle is properly detected.

Most railways use either track circuits or axle counters. Track circuits work by sending a current through the rails, which is short-circuited by a train’s axle. If the circuit is short-circuited, a relay drops, and the system knows that a block is occupied. Axle counters use induction to count the number of axles that enter and leave a block; if the same number of axles has left a block, it is unoccupied.

Lighter vehicles may have poorer wheel-rail contact than heavy trains. Furthermore, trams can have fewer axles than trains. Together, this results in a risk of loss-of-shunt (no detection of a vehicle) when track circuits are used (PZH, 2006). The Bombardier Flexity A32 trams used in the RijnGouweLijn trial were admitted to track-circuit tracks only in coupled use.

- Thorough testing of the detection of tram-train rolling stock with track circuits might result in no detection issues, in which case the rolling stock can safely be used on tracks with track circuit train detection.
- Axle counters do not rely on electrical contact between wheels and rails and are therefore not prone to loss-of-shunt due to poor wheel-rail contact. Using axle counters instead of track circuits for train detection is a full solution. From the RijnGouweLijn trial, it was learned not to use both track circuits and axle counters simultaneously for train detection. As both systems can fail, the combined use leads to a reduced availability (PZH, 2006).
- Track Circuit Assisters (TCA) can be mounted on rail vehicles. A TCA uses induction to increase the electrical potential between the wheelset and rail head, which improves the detection of trains by the track circuits, even when rail heads are affected by some rust (RSSB, 2014). However, in the RijnGouweLijn trial project it proved infeasible to use TCAs to improve the detection of the light rail vehicles. Due to the low floor, there is limited space to mount the device. Simulations showed that the low floor of the vehicle also damps the working of the induction coils (PZH, 2006).

Table F-12: Assessment of train detection solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Thoroughly test detection by track circuits	○	○	○	○
Replace track circuits by axle counters	●●	○	○	●●
Install TCA on tram-train vehicles	●	○	Existing: ○ New: ●	○

F.2.9.1 Sanding

Tram vehicles often use rail sanders at each powered bogie, to improve performance during acceleration and on steep inclinations. At heavy railways equipped with track circuits, the use of sanders may be restricted to the leading axles only to prevent loss-of-shunt (Carroll, 2018). In such cases, drivers should be able to select the correct set-up of sanding.

F.2.10 Pantograph – overhead line interface

F.2.10.1 Pantograph force

Novales & Conles (2012) note that there are differences between the vertical contact force exerted by the pantograph of light rail and heavy rail vehicles on overhead wires. When designing a tram-train vehicle, the maximum allowed force by the tram overhead lines and heavy rail overhead lines should be considered. Proper contact should be ensured at high speeds, while the required force for this should not exceed the maximum allowed force of single conductor tram overhead lines.

F.2.10.2 Moveable bridges / low tunnels

Moveable bridges or tunnels can be a discontinuity in the overhead lines. The pantographs of the light rail vehicles used on the Hoekse Lijn (Bombardier Flexity Swift) function differently than those on the trains that were used on the line. The train pantographs raise and descend slowly, while the pantographs on the light rail vehicles are ‘fast’. Therefore, the light rail vehicles cannot raise their pantographs while in motion, due to exerted forces on the overhead lines (Kats, 2018).

- Install mechanical pantograph guiding on the bridge or in the tunnel. The guiding can be built as permanently earthed sections, with neutral wires to guide the pantograph (Kats, 2018; Briggs, 2018).
- Equip tram-train vehicles with ‘slow’ pantographs, which can be raised and lowered while the vehicle is in motion.

Table F-13: Assessment of pantograph – overhead line interface solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Install mechanical pantograph guiding	●	○	○	●
Equip vehicles with ‘slow’ pantographs	●	○	Existing: ○ New: ●	○

F.2.10.3 Voltage changeover

Bi-current tram-train vehicles can be operated under two voltages. Between the tram and train network, a change from the tram current to the train current is made. The changeover can be performed automatically or manually by the driver.

- A basic solution is to have drivers manually perform the voltage changeover, by a selection button on the dashboard. This results in additional driver workload in the changeover area. See section F.5.1.
- In Karlsruhe, vehicles have a voltage detector on the vehicle. This sensor detects the voltage of the overhead lines and switches the voltage automatically.
- When tram-trains are equipped with ETCS, it is possible to send information about voltage changeovers to the vehicle via Eurobalises. The vehicle can use this information to switch voltage automatically. This situation becomes more expensive when multiple changeover areas are to be equipped with Eurobalises, or when the vehicle’s systems have to be modified to interact with the ETCS onboard equipment.

Table F-14: Assessment of voltage changeover solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Have the driver perform the changeover manually.	○		Existing: ○ New: ○	○
Equip vehicles with voltage sensing equipment.	●	○	Existing: ○ New: ●	○
Use trackside beacons to have trains change automatically.	●(- ●●) *	○	Existing: ○ New: ●	●

* Reference situation: a vehicle with manual voltage change.

F.2.11 Vibrations and noise

The different running characteristics (due to wheel size, profile and distribution) and increased weight of tram-train vehicles compared to regular trams can cause increased vibrations and noise on the tram tracks (De Vos, 2016). At locations where noise disturbance is already at a high level, tram-train vehicles might push this to an unacceptable level. In that case, it might be an option to reroute the tram-train. Technical solutions include modification of the tram wheel profile, or re-engineering of the tram tracks with noise and vibration-reducing measures (De Vos, 2016).

Table F-15: Assessment of vibrations and noise solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Reroute tram-train	○	●●	○	○
Modify tram-train wheels	○	○	Existing: ○ New: ●	○
Modify tram tracks	● - ●●	○	○	●●

F.2.12 Wrong-way movements

It should be prevented that non-tram-trains enter the connection chord between the heavy railway and the tram network. In Sheffield, this is solved by connecting the tram-train's vehicle information system (VIS) to the heavy rail interlocking. Only if the VIS proves that the vehicle is a tram-train, the signal towards the chord is cleared. To prevent trams from entering the heavy rail line, the point on the tramway auto-normalises to the tramway after each tram-train. Secondly, the vehicle can only get a proceed aspect onto the heavy rail line after the VIS confirms the vehicle to be in train mode (Carroll, 2018).

F.3 Infrastructure

Trams and trains run on the same principle: steel wheels on steel rails, with guidance by conical wheels and wheel flanges, with power from overhead lines. The interface between the two infrastructures consists of few components: a connection between the overhead lines, and a connection between the rails.

F.3.1 Power supply – neutral section

When the tram network and train network operate under different voltages and tram-train vehicles use both power supplies, a changeover section is required to connect the two overhead line networks. This changeover area should be at least as long as the longest vehicle using the section.

- Changeover can be performed while coasting through a neutral section. The risk of a vehicle stalling in the section should be minimised. Preferably, the neutral section should not be located in a sack. It should be possible to provide power to the section manually, in the event of a stalled vehicle. If a moving changeover is performed combined with a stationary tram – train changeover, space is required for a vehicle to accelerate sufficiently.
- Alternatively, voltage changeover can be performed stationary, by switching the voltage on the overhead lines. However, this process takes longer and requires automated switching equipment. On the other hand, less space is required, and the process can be combined with other changeover procedures. Moreover, there is no risk of a vehicle stalling in the section.

Table F-16: Assessment of voltage changeover solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Changeover while coasting through neutral section	○	○	○	●
Switchable section	●	●	○	●

F.3.2 Track gauge

F.3.2.1 Dual-gauge / gauntlet track

In this research, dual-gauge is regarded as a no-go criterion for tram-train. However, for short sections, dual-gauge might provide a solution to extend a network. Solutions for implementation of dual-gauge tracks are readily available, but not discussed in this thesis.

F.3.2.2 Allowing for future gauge changes

Novales & Conles (2012) note that the tram-train line in Cádiz is built with the gauge of the main line (Iberian gauge, 1668 mm), making it the first wide-gauge light rail line in Western Europe. However, there are discussions in Spain about changing to standard gauge. Therefore, the tram-train was constructed with polyvalent sleepers. This prepares the full track support to change to a different gauge in the future. For street tracks, a future track change will require additional street works.

F.3.3 Holding space between tram and train networks

In 4.5, it was pointed out that train operations are planned according to regular train paths, while tramways are operated on a headway base. Tram-train vehicles should enter the heavy rail tracks in an allocated path. However, if the path is missed, the tram-train should wait for a new path to be available. Therefore, it is important to have sufficient holding space between the tram and train tracks to prevent waiting vehicles from blocking back the tram network and possibly vice-versa, on heavily used tram tracks or intersections.

F.4 Infrastructure & Operational principles

Basically, the operational principles are confined to their infrastructure. On tram infrastructure there are tram operations (on sight) and on heavy railways, operations are according to heavy rail principles. Therefore, the interface between infrastructure and operational principles has few components.

F.4.1 Radio communications

On heavy railways, communication between vehicles and traffic control generally takes place via GSM-R, while most tram operators have their own communication system. In class C systems, it is possible to cover the heavy rail section by the tram communication system and control the section from the tram operational control centre. However, for tram-trains on shared lines, the traffic is likely to be controlled from a regional operational control centre. Still, the tram dispatcher might require contact with their drivers. To prevent contradictory information, there should be clear agreements. When the railway is equipped with ETCS L2 or higher, GSM-R radios are required in each vehicle.

F.4.2 Left-hand railway traffic

Tram drivers are used to operating their vehicles on-sight, and especially in ROW B/C alignments, drive on the same side of the road as road traffic. However, in several countries, trains run on the left tracks. Moreover, double-track railway signalling systems can generally handle traffic in two directions on both tracks. During disturbed situations, it is possible to invert the driving direction between the tracks.

However, Vreeswijk (2018) notes that in the beginning phase on the RandstadRail, tram drivers were hesitant of driving at full speed at the opposite track, as this was against their nature. Therefore, it is advised to include such situations in driver training.

F.4.3 Trespassing at stations

In low-floor tram operation, it is easy for passengers to step off a platform and cross the tracks to the other side. In on-sight operations, tram drivers are aware of this risk and drive cautiously at stops they do not call. However, at train lines, passengers are not allowed to cross the tracks, as non-stopping trains will not be able to come to a stop in time. Therefore, passengers should be discouraged from crossing the tracks.

- A cheap and easily implementable solution is to place a fence between the tracks. However, fences are not a fail-safe solution, as passengers can climb over them.
- Low-floor platforms can be equipped with platform screen doors (PSDs), which only open when a vehicle is stopping. This requires drivers to stop at a precise location. On the other hand, PSDs are also effective in keeping passengers away from the platform edge when regular trains are passing the platform (Carroll, 2018).
- Anti-trespass grids can be placed on the rail bed (Carroll, 2018).

Table F-17: Assessment of solutions which prevent trespassing at stations.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Fence between the tracks	●	○	○	Rail: ○ Stations: ●
Platform screen doors	●●	●	○	Rail: ○ Stations: ●●
Anti-trespass grids	●	○	○	Rail: ● Stations: ○

F.5 Operational aspects

It was found that on tramways, drivers are fully responsible for driving safely (on-sight operation). They can be supported by signals and other systems. On heavy rail lines, the safety is guarded by the interlocking system. The driver must adhere to signal aspects and be in contact with traffic control. The interface between the two principles occurs in the changeover section. In section 4.5, a subsection was dedicated to outlining differences between operational aspects of tram and train systems. Here, one additional issue is highlighted.

F.5.1 Changeover zone: driver workload

In transition zones, drivers might be required to perform several tasks in a short timeframe, such as interacting with the ATP system, selecting the right power supply, and contacting traffic control. In Kassel, the changeover from tram to train takes place during the stop at the main station (NVV, 2006). In Sheffield, the changeover is performed while stationary at the connecting chord. Here, the driver should change the operating mode by means of a physical switch. Also, the driver should contact the rail traffic control via GSM-R. While stationary, the driver can focus on the changeover procedure. If all changeovers are performed, the signal is cleared, and the tram-train can enter the heavy railway line (Carroll, 2018).

However, if the changeover occurs while moving, the driver should be able to perform the changeover tasks and keep an eye on safe operation at the same time. In Karlsruhe, the vehicles change voltage automatically, and the BOStrab – EBO changeover is merely regulatory, without a physical aspect. Depending on whether the vehicles enter tracks of DB, contact should be made to the traffic control of DB. Still, the changeover requires only some driver action.

F.6 Operational aspects & Rolling stock

Tram-trains should be able to operate as a road vehicle on tram sections, and as a train on the train lines. This sets requirements to the vehicle design, but also creates certain possibilities.

F.6.1 Vehicle length

According to the BOStrab regulations in Germany, tram vehicles on ROW C sections may not be longer than 75 meters. This limits the total capacity of a train. Existing tram networks can have stricter length limits, due to platform lengths or traffic constraints.

When the changeover area between street running and train running is located near a train station, it is possible to add or remove a unit from a train when calling at the station. The advantage of this is the additional capacity that can be offered on the heavy rail line, for example to serve people who use the tram-train as regional train. Also, a tram-train can be split on the station and run to two different destinations within the city. If a holding track near the station is present, this can reduce the need for empty trips, and temporarily hold vehicles without blocking platform space.

The downside of the combining process is an increased dwell time, and high required timetable reliability. Moreover, couplers add weight to vehicles. As the couplers might need to be stowed for safety reasons while in street running mode, the stowing process can negatively impact vehicle reliability and availability (Donders, 2018). In Karlsruhe, this issue is partly resolved by only stowing the front couplers.

Table F-18: Assessment of combining vehicles.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Combine vehicles at a station, and run in single traction in the city	●	●●	Existing: ○ New: ●	Rail: ● Stations: ●

F.6.2 Postponed braking regimes

In the RijnGouweLijn trial, it was observed that the improved braking performance of the tram-train vehicles could lead to travel time improvements. The Dutch signalling system prescribes that drivers should obey a signal immediately. However, the lower maximum speed and braking performance meant that trains lost time by driving slower than necessary at a certain location. Due to the braking curve supervision of ATB-NG (and similar ATP systems), it is possible to postpone braking until required by the braking curve. This way, time can be saved without impacting safety (PZH, 2006).

F.6.3 Vehicle lights

Trams and trains have different specifications for front and tail lights. For trams, they should be road-legal; with dipped head lights, brake lights and turn indicators. On train lines, lights should be brighter, such that they can be seen from a larger distance. The space separation from block systems makes the use of brake lights and turn indicators unnecessary.

- The light units for tram-train can be designed to house two sets of lights; separate lights for tram operation and for train operation. This way, all lights can be fully compliant to the relevant standards. However, this requires more space for the light units.
- In Sheffield, the lights were designed in such a way that single light sources could be compliant to both tram and train regulation. The tram brake lights double as tail lights on the train network,

while the front lights can be dipped for tram and night-time train operation, or full beam for daytime train running (Carroll, 2018). However, this option might not suffice in all countries.

Table F-19: Assessment of vehicle light solutions.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Two light units	●	○	Existing: ○ New: ●	○
Combine lights	○	○	Existing: ○ New: ○	○

F.6.4 Toilets

Generally, urban public transport vehicles have no toilets, as passengers generally spend a very short time in the vehicle. However, in tram-trains, passengers might spend more time. Therefore, in some regions it has been decided to build toilets in the vehicles (Chemnitz, Karlsruhe). However, toilets reduce passenger space and increase the vehicle weight and design complexity.

Table F-20: Assessment of providing toilets in vehicles.

Solution	Cost	Operations	Rolling Stock	Infrastructure
Include toilets in the vehicle	●	●	Existing: ○ New: ●	○

F.7 Operational aspects, Rolling stock & Infrastructure

F.7.1 Evacuation

Low-floor vehicles can be evacuated without additional equipment. However, in a heavy rail environment, it is potentially very dangerous to evacuate on the open track. Therefore, if tram vehicles are equipped with automatic door releases after an emergency brake, this should be overridden while on the heavy rail line. The decision to release the doors should be left to the driver’s discretion.

F.7.2 Station design

In addition to the physical design of platforms at train stations (see section F.2.1), there are also operational consequences when the tram-train rolling stock requires different platforms than trains. If services that are replaced by tram-train services move to a different platform in the station, caution should be paid to time-tabling. If the relocation of a certain service makes a cross-platform transfer impossible (e.g. to a long-distance service), additional time should be scheduled (PZH, 2006). Moreover, it should be made impossible for passengers to cross the tracks, as discussed in section F.4.3.

At the 4-track tram stop at the main station in Karlsruhe, the unidirectional trams stop at the inner two tracks, with island platforms between the inner and outer tracks. The tram-trains use the outer tracks and have platforms on both sides of the vehicle. This way, an efficient transfer to both the trams and towards the main station forecourt can be provided. However, the tram-trains form a barrier between the trams and station forecourt. It is observed that tram passengers walk through the tram-train towards the forecourt, risking becoming ‘trapped’ in a departing vehicle.

G. Manual for the Tram-Train Implementation Support Tool

This manual provides additional information on the criteria processed in the T-TIST. Users can refer to this document to gain more understanding of the required input data.

G.1 Quick scan

In the quick scan, a rough estimation of the implementable classes is made, and it is indicated how tram-train could be used next to other heavy rail services. Table G-1 lists all the required inputs, with some guidance on the required values. Below the table, some criteria are explained in more detail.

Table G-1: T-TIST input variables.

Input variable	Input value	Notes
Population and corridor		
City population	Number of inhabitants in thousands	The population of the main city.
Corridor population	Number of inhabitants in thousands	The population of the settlements with stations along the proposed corridor. Neighbourhoods of the main city need not be included.
Corridor population spread type	Type A – E	The spread types are outlined below.
Corridor length	Km	The track length of the proposed corridor, starting from the changeover between tram and train.
Low-density section population	Number of inhabitants in thousands	The total population of the settlements along the low-density section of the corridor; relevant for population spread type *A* and *C*.
Low-density section length	Km	The length of the low-density section of the corridor; relevant for population spread type *A* and *C*.
Presence of high-quality rail modes along corridor	Yes / no	Are there high-quality rail modes along the corridor, into the city (metro; S-bahn/RER)?
Line envisioned as feeder	Yes / no	Will the proposed line serve as a feeder to higher-level modes?
Infrastructure		
Heavy rail infrastructure present	Yes / no	Is there heavy rail infrastructure present along the proposed corridor?
Tram infrastructure present and usable	Yes / no	Is there a tram network in the city, and is this usable for the tram-train?
Possibility of constructing a new tram line	Yes / no	Is it acceptable to construct a complete new tram line for the tram-train?
Heavy rail usage		
Number of available train paths	Trains per hour per direction	Should be entered if known.
Regional trains	Trains per hour per direction	An indication of the current number of hourly regional trains in each direction should be given.
Intercity trains	Trains per hour per direction	An indication of the current number of hourly intercity trains in each direction should be given.
Freight trains	Trains per hour per direction	An indication of the current number of hourly freight trains in each direction should be given.
Can tram-train replace regional trains	Yes / no	Can the tram-train service replace the present regional rail service.

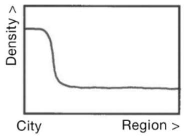
Input variable	Input value	Notes
Railway layout	Type A – F	Type according to Table 5-7.
Length of shared section	Km	The length of the section which is shared by the tram-train corridor and heavy rail services. This value can deviate from the corridor length when parts of the section will be used for tram-train only. This figure, however, cannot exceed the corridor length.

Population

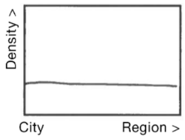
The entire population should be considered, including areas which are not connected to the tram(-train) network. For all settlements along the regional corridor the entire population should be considered, even if outside the catchment area of stations.

Choosing population spread type

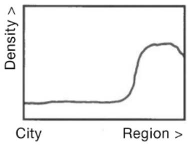
Contrasting to the corridor length, which is determined from the changeover point, the population spread should be considered from the edge of the city.



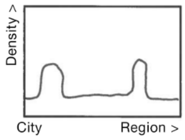
A) A higher population density near the city ("voorstad") and a smaller population towards the end of the corridor.



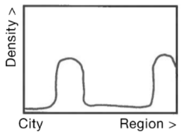
B) Even spread (continuous housing) or several villages/towns with a similar size along the corridor. Spread type E with short distances between towns is likely to be classified as spread type B.



C) A significantly larger town at the end of the line, compared to the intermediate section.



D) A clear distinction between some larger villages along the line, and smaller settlements. The larger villages need not be 'real' towns, but they should be significantly larger than the small settlements with a stop. If there are no settlements with stops between the towns, the spread type will likely be *B* or *E* (if more than 5km apart).



E) Few cores, with little to no population in between. Should only be chosen if almost all towns are more than 5 km apart. Otherwise, the spread type will likely be B or D.

Other rail corridors into the city

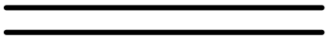
This criterion specifically concerns rail corridors which run through the city centre or other main attraction centres, such as most metros or S-Bahn. Rail corridors that serve more stops than regular trains (typical commuter trains), but do not serve attraction centres directly should not be regarded for this criterion.

Track layout

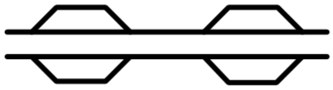
The six provided track layouts are typical layouts, to which variants exist. For instance, the track allocation of class E (four tracks) can be inverted, with the regional trains utilising the centre tracks. A different layout, which is not included in the T-TIST is triple track, where the third track is used to hold trains while they are being overtaken by faster trains. This increases the capacity but requires high punctuality as the centre track can be used in two directions. Double-track lines with triple-track sections can be inputted as layout D if reliable possibilities for overtaking can be provided without compromising travel time. Otherwise, it should be inputted as layout C.

A) Single track.

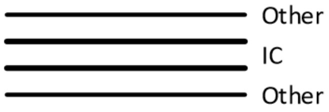
B) Single track with passing possibilities.



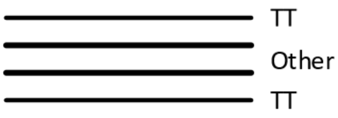
C) Double track. Also, triple track without reliable overtaking possibilities



D) Double track with overtaking possibilities. Also, triple track with reliable overtaking possibilities, and layout E with sufficient crossovers for overtaking purposes.



E) Quadruple track, with dedicated tracks for intercity and other services. If crossovers are available and overtaking is possible, layout D should be chosen.



F) Quadruple track with two dedicated tram-train tracks.

G.2 Suitability scan

The T-TIST provides brief instructions about the required inputs for each criterion. Some criteria require additional information, which is given in this section.

Criterion 1.1; population density around stops.

The population density around stops translates the inhabitants per line-km into a more specific value. An estimation for the entire line should be made.

A. Very low density: Widely spaced housing (bungalows / villas) or very small settlements. Stations not near housing.
B. Low density: Small settlements, spaced housing. Stations outside towns.
C. Medium density: Stations on the edge of larger towns (around 7.5K inhabitants or more), or in the centre of small towns (up to a few thousand inhabitants). Also relevant for small towns with significantly higher residential density near stops.
D. High density: Stations in the centre of towns with around 7.5 thousand inhabitants, or on the edge of larger towns (over 20 thousand inhabitants).

Criteria 4.9, 4.10; attraction centres

For the attraction centres, it is important not to double-count attraction centres. A separate sub-criterion is provided for large educational facilities, such as large high schools, universities and colleges. These facilities typically produce a large transport demand and should be excluded when determining other smaller attraction centres along a corridor (sub-criterion 4.9). Small attraction centres can include, amongst others, small schools, hospitals, museums, sports facilities (which can have a very large demand at times) and smaller shopping centres.

Criteria 5.14, 5.15; attractiveness of the walking corridor

When valuating this criterion, one should not include a length component, but confine to the physical appearance and traffic nuisance. The length (and possibly height difference) have been captured separately in sub-criteria 5.12 and 5.13 and should not be included twice.

A. Very attractive: Through a park or indoors (shopping mall).
B. Attractive: Calm streets, not too busy crossroads.
C. Neutral: Regular pavements, some crossroads.
D. Unattractive: Narrow pavements, unattractive appearance, some busy crossroads.
E. Very unattractive: narrow sidewalks and several very busy crossroads along the route. Unattractive appearance.

The sub-criterion on poor personal security can be used when pavements are lacking, or when for instance a park is experienced as unsafe at night.

Criteria 6.17, 6.20; connection between tram and train network

A. Poor availability: The connection can be made at some place, but not at a logical site (requiring a detour) or requires demolition of buildings.
B. Neutral availability: There are a few possible locations for a connection.
C. Good availability: There is an obvious location (clear and empty space) for the connection, or there are several possible locations.

The penalty criterion (6.20) is based on the constructability and layout (such as lines-of-sight, vertical alignment) of the connection.

Criterion 7.27; platform gap

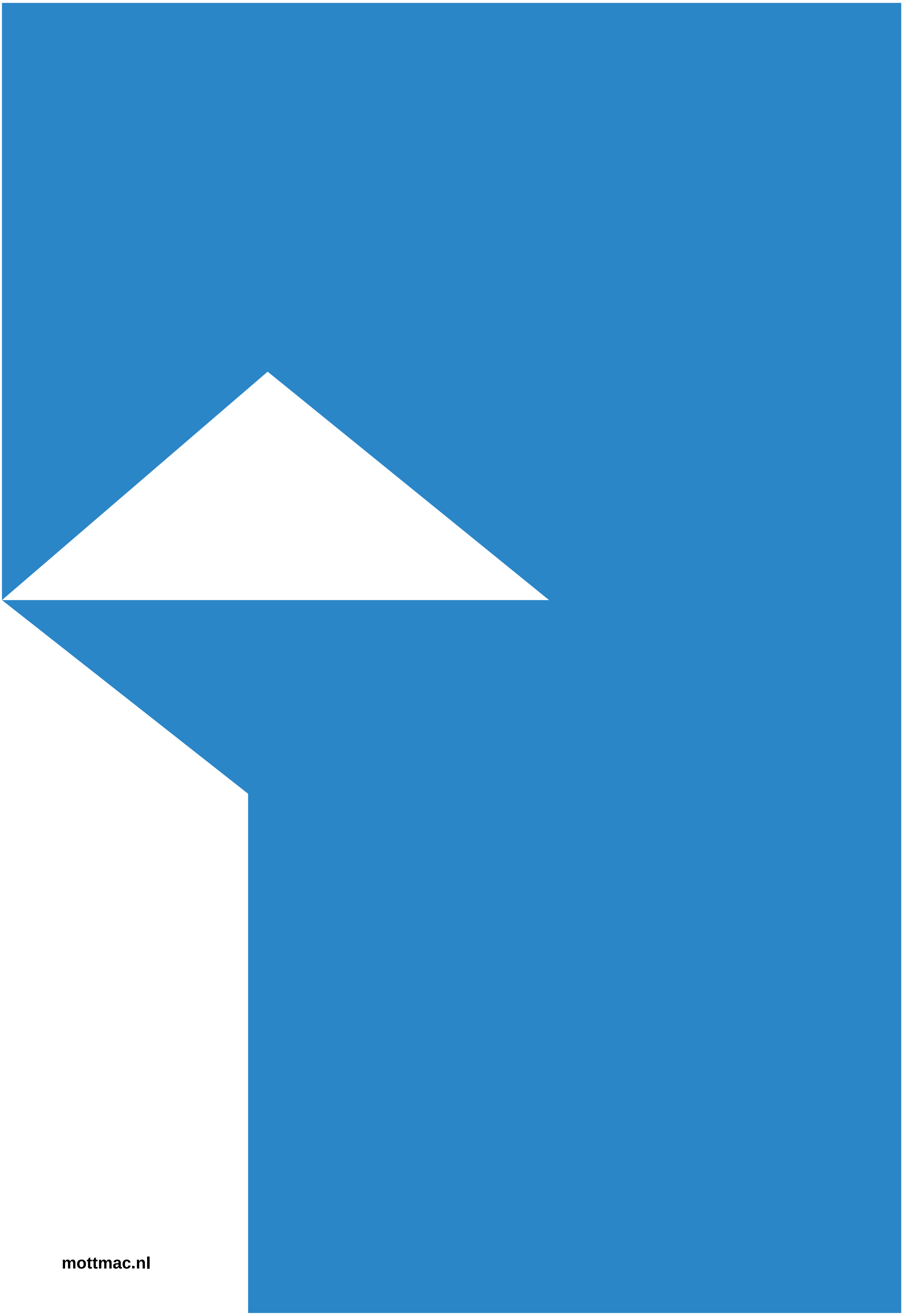
In case tram-train vehicles will be wider than the existing tram fleet, the platforms might need to be adapted. If the existing fleet is still used along the alignment, there is a risk that the gap between the vehicles and platforms is widened. This criterion is only relevant if the accessibility to the trams decreases. For high-floor vehicles at low platforms, the gap will not be an issue.

Criterion 9.39; pedestrian area

Tramways in areas with many crossing cyclists (such as educational campuses) can be penalised as having short pedestrian areas. As cyclists tend to disobey traffic rules, they might hinder undisturbed operations.

Criterion 11.48; height component of transfers

Most large stations have over- or underpasses over the tracks, and as such a height component is always included. To distinguish between such facilities, this criterion should be used when the tram platform is at a different level than the train platforms.



mottmac.nl