Analysis of Tram Systems and Their Implementation in Wiesbaden

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ANALIZA TRAMVAJSKIH SUSTAVA I NJIHOVA IMPLEMENTACIJA U GRADU WIESBADENU

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DIPLOMSKI RAD / MASTER THESIS

Wiesbaden, Zagreb, 2018.

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Zadatak: **Analiza tramvajskih sustava i njihova implementacija u gradu Wiesbadenu**

Opis zadatka:

U diplomskom radu potrebno je analizirati primjere gradova u europskom okruženju koji su uspješno implementirali različite oblike tramvajskog prijevoza, prikazati budući plan tramvajske mreže u Wiesbadenu, također analizirati troškovnu korist za implementaciju nekih varijanti i njihovu opravdanost u Wiesbadenu.

Mentor:

doc. dr. sc. Marko Slavulj

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Predsjednik povjerenstva za diplomski ispit:

Sveučilište u Zagrebu

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Faculty of Arhitecture and Civil Engineering

Wiesbaden

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ANALYSIS OF TRAM SYSTEMS AND THEIR IMPLEMENTATION IN WIESBADEN

Mentors: Prof. Dr. Ing. André Bruns
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Wiesbaden, Zagreb, lipanj 2018.

SUMMARY

An analysis of modern tram systems using catenary-free technology has been carried out, mainly ground-level power supply system, induction tram system, battery system and super-capacitor system. An analysis of the current situation and the public transport system in Wiesbaden has also been made, which is heavily based on bus transportation. Due to the maximum utilization of bus transportation capacty for the provision of passenger transport services and the impossibility of additional expansion, it is necessary to implement a tram network in the city. Since it is a city of great historical heritage it is necessary to preserve the aesthetics of the city and therefore consider introducing some of the catenary-free technologies. Based on the project analysis made, options were offered for the implementation of CityBahn and a cost-benefit analysis was developed for each one to gain insight into the cost-effectiveness of such investments.

Keywords: tram, tram network, ground-level power supply, induction tram, battery system, super-capacitor, Wiesbaden, CityBahn, catenary-free, cost-benefit analysis

SAŽETAK

Provedena je analiza suvremenih tramvajskih sustava koji primjenjuju „catenary-free“ tehnologije odnosno tramvaje bez kontaktne mreže. Analizirani su sustavi koji koriste napajanje putem vozne površine (treća šina), indukcijski tramvaji te tramvaji nadograđeni baterijskim i superkondenzator sustavima. Također je napravljena analiza trenutne situacije i sustava javnog prijevoza u Wiesbadenu, koji se trenutno temelji na autobusnom prijevozu. Zbog dostizanja maksimalne iskoristivosti kapaciteta autobusnog prijevoza te nemogućnosti dodatnog unaprijeđenja sustava, donesena je odluka o izgradnji tramvajske mreže. Budući da se radi o gradu velike povijesne baštine, potrebno je sačuvati estetiku grada i stoga se razmatra uvođenje tramvajskog sustava koji eliminira naponske vodove iznad tramvaja. Na temelju izrađene analize projekta, ponuđene se lokacije te odgovarajuće tehnologije pogodne za implementaciju na CityBahn-ovu tramvajsku mrežu. Kako bi se dobio uvid u isplativost takvih ulaganja napravljena je analiza troškova i koristi za svaku ponuđenu opciju implementacije.

Ključne riječi: tramvaj, tramvajska mreža, napajanje putem vozne površine, indukcijski tramvaj, baterijski sustav, superkondenzator, Wiesbaden, CityBahn, catenary-free, analiza troškova i koristi

CONTENT

1 INTRODUCTION

The decision-making process and choice between transportation systems is not only in technology but also in the type of services, its image and impact. Therefore the decision-making processes for tram or light rail involves great technical and social complexity, making each project unique but at the same time similar in regards to the policies, frame, and objectives around these projects. For instance, the decision between implementing a tram system, light rail system or a bus transit system must be taken according to the advantages each system brings to the mobility of the city.

The tram or light rail solution, besides being financially beneficial comparing to many other systems reduces traffic congestion and restructures mobility in and around cities, generating urban development in city centers and suburbs. Finally, tram or light rail is a good solution for reducing vehicle dependence, traffic congestion, energy consumption and pollution.

The aim of this master's thesis is to analyze modern and alternative tram systems and see which of the systems could be implemented on the future tram network in Wiesbaden to meet the city's demands in the most cost-effective way. The paper is divided into the following chapters:

1. Introduction
2. Analysis of Alternative Tram Systems Used in European Cities
3. Analysis of the Existing Public Transport Network in Wiesbaden
4. Project Analysis of the Future Tram Network in Wiesbaden
5. Implementation of an Alternative System on the Future Wiesbaden Tram Network
6. Cost-Benefit Analysis of an Alternative Tram System Implemented in Wiesbaden
7. Conclusion

In the second chapter, various tram systems have been described which have so far been applied in European cities. Technologies that are studied are ground-level power supply, inductive trams, battery systems and super-capacitor tram systems.

The third chapter deals with the analysis of the current traffic situation in Wiesbaden. The traffic flow in the area of the city was analyzed as well as the coverage of public transport lines. It is also possible to see the population growth forecast as well as the daily demografic gravity in the city area.

The fourth chapter analyzes the route plan of the tram lines and plans for their construction. The city's demands are presented and the budget estemated to achieve them.

In Chapter Five, potential catenary-free locations were selected and, according to their needs, technologies that meet these requirements with the highest cost-effectiveness. There are also examples of vehicles that meet the CityBahn requirements.

In Chapter Six, a cost-benefit analysis was carried out of the conventional tram system as planned on the network as well as for the potential catenary-free systems that were selected in the previous chapter. The purpose of the chapter is to gain insight into the costs and possible justification of such investments.

2 ANALYSIS OF ALTERNATIVE TRAM SYSTEMS USED IN EUROPEAN CITIES

Some areas in the city centres or urban zones need to preserve the characteristics of historical buildings or have cross sections such as bridges and tunnels. This means that trams running without an overhead line are a great solution which can benefit both the city councils and transportation bureaus. [9]

2.1 ALIMINATION PER LE SOL (APS)

APS is a service-proven solution for catenary-free tramway operation which preserves the aesthetics of city centers, reduces LRT systems footprint by eliminating poles, and optimizes safety and operation reliability. The key advantages are; no electrical power limitation, no risk of running out of power in degraded operation mode, full compatibility with all types of road and track-bed surfaces, and easy line extensions. [1]

This type of tram system is used in the following cities:

1. Bordeaux, France
2. Reims, France
3. Angers, France
4. Orléans, France
5. Tours, France
6. Dubai, United Arab Emirates
7. Rio Porto-Maravilha, Brazil

And in the process of construction in following cities:

1. Cuenca, Ecuador
2. Lusail, Qatar
3. Sydney, Australia

2.1.1 **TECHNOLOGY**

APS rail technology is distinct from most other methods of supplying power to trams. Instead of picking up power from a conventional overhead wire, the system uses a third rail placed centrally between the riding rails to transfer power to the tram. The rail is broken into two types of segments: neutral segments (~3m) and powered segments (~10m).

Trams riding over the third rails utilize power shoes or skates to collect electricity from the powered rails, which are only activated when special radio antennae under the tram signal these rail segments to energize. Thus, only the segments directly under the moving tram which have been signaled by the undercar antennae will be electrified at any one time. This system is visualized below in Figure 1. [2]

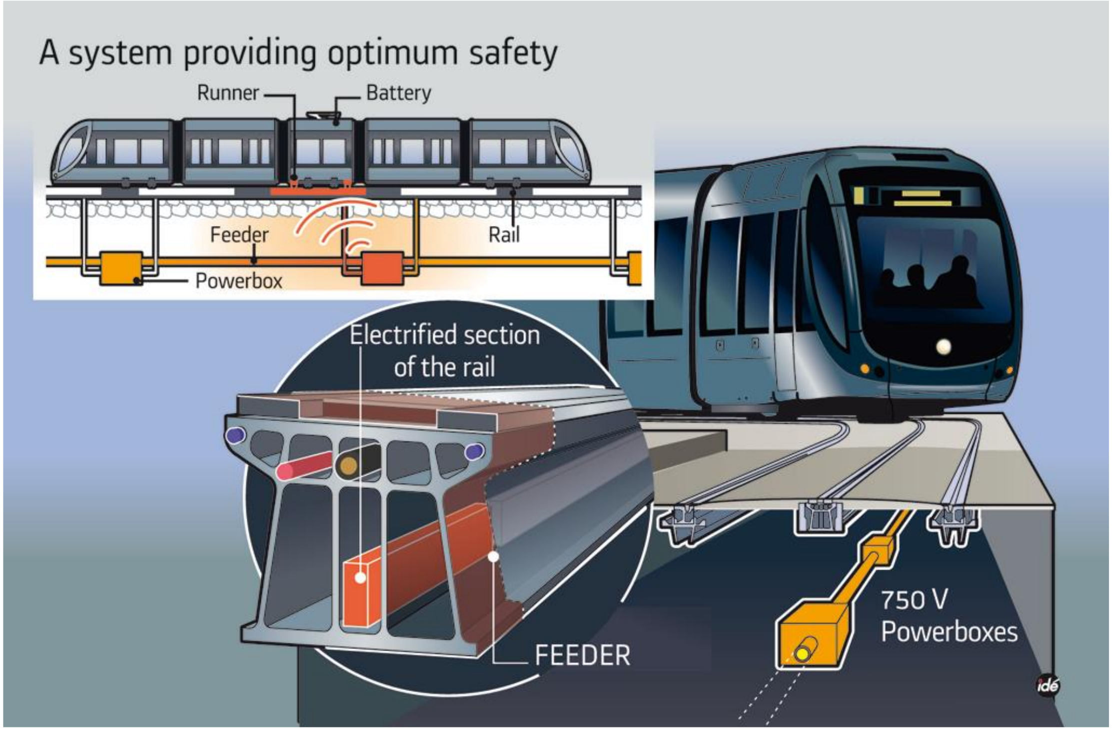

Figure 1. APS track/tram interaction and visualisation of the electrified section of the rail

Source: [2]

APS main components are:

1. Switching cubicle which allows switching the power source between APS, catenary or back-up battery.

2. Contact shoes which collect traction current from the 750 V conductor rail segment.
3. Antennas that emit a coded radio signal which allows detection of the vehicle by the adjacent power unit through a detection loop embedded in the third rail.
4. Back-up battery unit which enables the tram to run in the event of power cuts to secure operation performances.

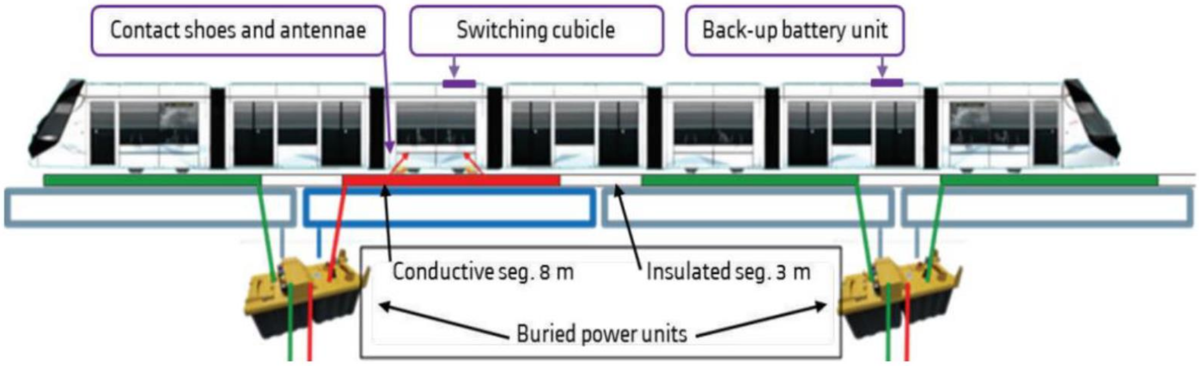

Figure 2. APS main components

Source: [1]

Power is supplied to the tram vehicle through a segmented street-level power rail embedded between the running rails in the axis of the track. Conductive segments are switched off/on/off as the tram progresses, ensuring total safety for pedestrians. The APS third rail is made of 8 meter-long conductive segments separated by 3-meter insulating joints. Power is supplied to the conductive segments by buried power units. The electricity transmitted through the third rail is picked up by two contact shoes located on both sides of the tram central bogie as visualized in Figure 2. [1]

2.1.2 **BORDEAUX, FRANCE APS TRAM NETWORK**

Bordeaux’s Light Rail system is a standard-bearer for modern light rail systems due to its ease of use, aesthetics and seamless surface integration. Bordeaux’s exceptional architectural quality and coherence has been recognized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a World Heritage site, in France second only to Paris in the number of protected buildings (327). The Bordeaux tram system was designed, in part, to protect and complement the historic core.

The system was envisioned to improve the transportation system for the people of Bordeaux and its suburbs, using the newest technologies in a manner that respected the architectural significance of downtown Bordeaux. The tram rights-of-way are a mix of grassy medians or clearly delineated areas on existing road surfaces.

The system is street-based but separated from traffic except at intersections. The Bordeaux tram network consists of 3 tram lines shown in Table 1 as the main form of public transport serving the city center and 78 bus lines used mainly for collecting passengers and transmitting to the tram network with the exception of a couple of bus lines which also operate's in the city center. [2]

Table 1. Bordeaux tram lines specifications

LINE	LENGTH	STATIONS	ROUTE
A	20.6 km	41 stops	Mérignac Centre - La Gardette Bassens Carbon Blanc and Floriac Dravemont
B	15.2 km	32 stops	Pessac Centre - Berges de la Garonne
C	8.1 km	17 stops	Terres Neuves - Berges du Lac
-	-	-	14 km total APS tramway between lines

Source: [2]

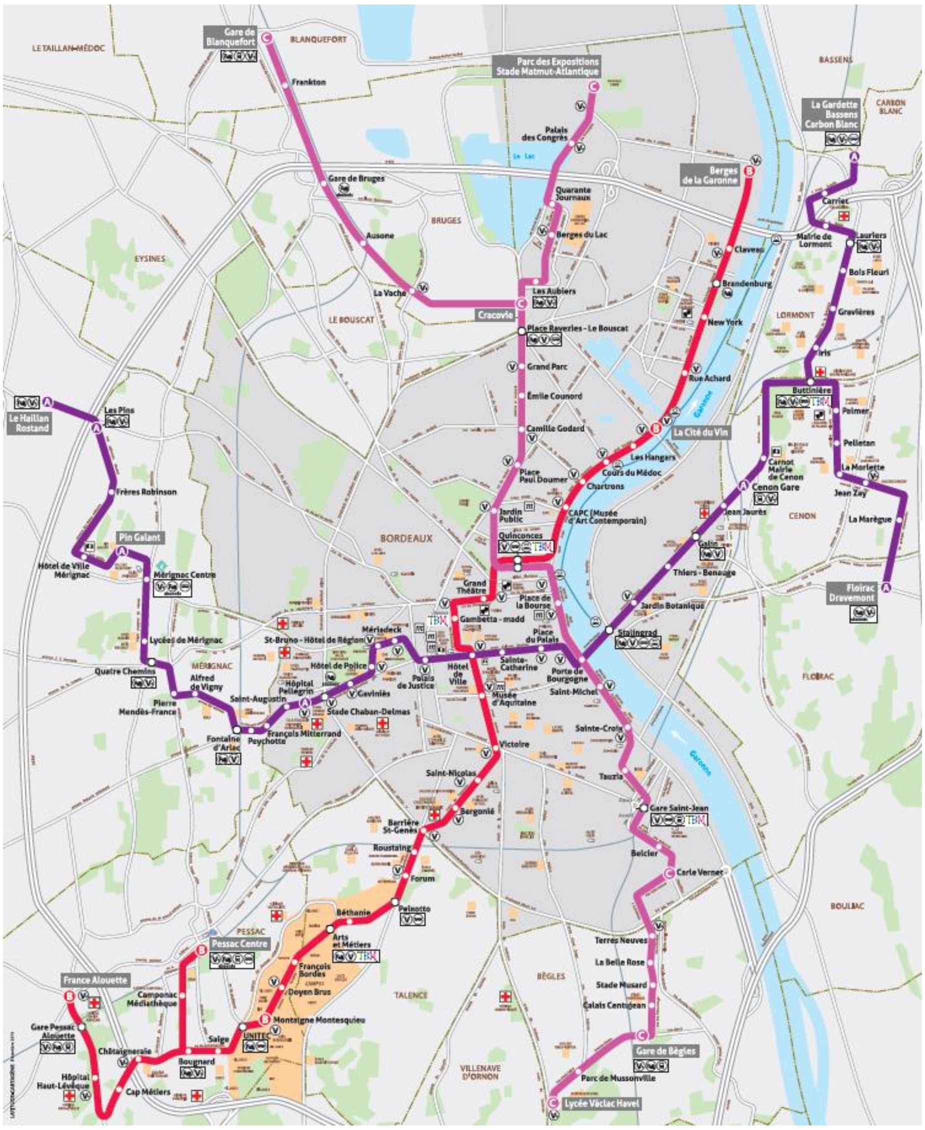

Figure 3. Bordeax tram network

Source: [4]

Line A: runs from East to West, after crossing the Garonne River on a bridge (Figure 4), it splits into two lines heading to the North and South part of the City.Line B: runs from the Northeast to the Southwest. Line C: runs from the North towards the Southeast area of the City. Figure 3. There are seventeen park and ride locations with a total of 5,000 parking spaces. In the historic downtown, 1.8km of the tram system was designed without an overhead contact system (OCS) as shown in Figure 5. [21]

Figure 4 Estetic of Pont de pierre bridge after implementation of APS

Source: [22]

Figure 5 Historic city centar in Bordeaux

Source: [22]

In Bordeaux, transitions from INNORAIL to conventional OCS (and vice versa) are manually initiated by the vehicle operator with the vehicle stopped at a passenger platform. This transition is completed within normal station dwell times. According to the manufacturer, it is also possible for this process to be automated, allowing the transition to be accomplished with the vehicle moving. [7]

INNORAIL System Components are separated in two basic groups, fixed installations and vehicle components. The fixed installation part of the INNORAIL system is made up of the following elements:

1. Sectional power rails (as mentioned earlier), these low profile sections are typically in 11 m lengths fitted with 8 m of conductor rail and 3 m of insulating rail. These FRP pultrusions contain integral duct banks that carry all power, ground and control cabling., as well as the vehicle detection loop for that section. These assemblies also have a spare cable duct that could potentially be leased to local fiber optic or coax cable service providers. The ratio of conducting rail to insulating rail is based on the vehicle operating speed, which in the case of Bordeaux is 20m/sec or 72 km/h.
2. Power rail control contactor units, one is located every 22 m, and controls two segments of power rail. These units are modular and can be replaced in less than 5 min. Although a solid state switching unit would logically be utilized, traditional contactor units were chosen for this application because the short duty cycles caused difficulties in semiconductor heat rejection at these current levels.
3. Insulating junction boxes, an insulating joint box is located every 22 m to mechanically and electrically join the ends of the power rails at all locations. These boxes are silicone sealed after all connections are made to keep out moisture.
4. Grounding contactor and system monitoring equipment for safety purposes, a cabinet containing a grounding contactor and system monitoring equipment is installed in each substation. The condition monitoring system is designed to detect faults in any power rail segment within 200 milliseconds, disconnect and ground the main 750 V/dc power feeder to all segments fed by that substation, automatically isolate the faulty segment and restore the system power to the remainder of the system in less than 2 seconds. These faults include, most importantly, a segment

remaining live after the vehicle signal is lost and of course, short circuit or similar faults. [7]

The INNORAIL system is capable of being installed on almost any type of light rail vehicle, including 100% low-floor vehicles. The following additional equipment is required to operate on an INNORAIL equipped system:

1. Emergency battery set one roof mounted unit is required on each vehicle to allow it to transition through any dead power segments. To save space, this unit is mounted under the pantograph frame on the vehicle center section. This battery set contains 63x12 volt sealed, aircraft certified, lead acid batteries and can provide approximately 1 min of vehicle movement at reduced speed 3 km/h. This will move the vehicle a minimum of two failed power rail segments, although 152 m is routinely achieved.
2. Retractable power pickup shoes, two sets of center truck mounted pickup shoes are necessary for current collection, mounted at the ends of the truck. The shoegear uses graphite shoes to keep the fixed installation wear to a minimum, although in the initial stages, soft iron shoes have been used to clean and polish all the contact surfaces.
3. Pickup shoe control box, extra control components required to activate the pickup shoes and interlock with the pantograph controls.
4. Power control box, this roof mounted box contains the additional contactors and controls needed to for switching 750V/dc power coming from the pickup shoes or the emergency battery set.
5. Cab controls and monitoring equipment, which are additional controls required to operate and monitor the vehicle's INNORAIL related equipment.
6. Safety grounds, extra ground points installed under the low-floor section of the vehicle to suppress any possible fault conditions. [7]

2.1.3 ROLLING STOCK

Alstom has applied a ground-level power-supply system (APS), a third rail embedded among the tracks, for their Citadis trams. The APS ground-level power supply system allows trams to travel without overhead catenaries, and integrate harmoniously into the urban landscape. However, the main goal of this system is to preserve the urban environment and the region’s historical heritage, not to focusing on improving energy efficiency. Moreover, the APS are rather expensive, costing more than a catenary-based powering system. [8]

The Bordeaux fleet consists of the Alstom Citadis X02NG vehicle series that are designed to be compatible with APS technology. The name is composed as a code: the letter NG are for New Generation, while X02 contains information about the length of the tram. It is proposed in three lengths versions:

1. 40 meters long for X=4
2. 30 meters long for X=3
3. 20 meters long for X=2 [23]

The Bordeaux fleet consists of the models 302 and 402 shown in Figure 6 and with the specifications shown in Table 2.

Figure 6 Alstom Citadis 302 i 402 tram model, Bordeaux

Source: [20]

Table 2 Alstom Citadis 302 and 402 tram specifications

Model	302	402
Manufacturer (mechanical part)	Alstom	Alstom
Manufacturer (electrical equipment)	Alstom	Alstom
Wheel arrangement	Bo Bo + 2 +	Bo + Bo + Bo +2
Engine performance	4 x 120 kW	6 x 120 kW
Maximum speed	70 km/h	70 km/h
Length (body)	32,846 mm	43,989 mm
Width	2,400 mm	2,400 mm
Height	3,270 mm	3,270 mm
Bogie center distance	11,143 mm	11,143 mm
Wheelbase	1,600 mm	1,600 mm
Floor height	350 mm	350 mm
Entry height	320 mm	320 mm
Light door width	800 / 1,300 mm	800 / 1,300 mm

Empty weight	41,340 kg	54,920 kg
Seats	48	70
Standing room (4 pers./m²)	170	230
Transport capacity	218	300

Source: [24]

Citadis X02NG Tramway presents several peculiar characteristics:

1. It is a modular vehicle made by several cars that can be composed in order to meet customer's requirements (plug-and-play logic). It is sold all over the world, adapting itself to very different environmental and service conditions.
2. It's a 100% low-floor vehicle able to operate with 20 meters minimum curve radius.
3. It has several optional packs that can be integrated on the vehicle, modifying architecture and power consumptions.
4. It's cost-oriented, it means with a strict orientation to reduce fix and variable costs, and weight-oriented, in order to reduce the gap with the main competitors and to join the 10 tons per axle target imposed by the German market.
5. Because of safety reasons, LV level is 24 V. This very low level makes distribution system critical in respect of voltage drops' limits.
6. The new electrical architecture has been improved to achieve the 0 V voltage drops goal.
7. In all Citadis X02NG versions there is no redundancy on CVS and battery (only in 40 meters version a smaller ventilation CVS is added).
8. It has a predisposition for the new Eco pack and APS (ground rail supply) systems implementation. [23]

The low voltage architecture has been developed for the X02NG model trams to allow the deletion of low voltage boxes on the roof, in order to leave enough space for the Eco Pack equipment's - chopper box and super capacitors boxes - that permits the braking energy saving and to perform parts of the track with the lack of the primary HV supply. This led on designing a new based on end-boxes situated on the roof of each car to realize a local electrical distribution for each car. [23]

There are also newer generation Alstom trams that are also compatible with the APS system, one of which is the latest Citadis X05 model used in Nice on another type of tram system described in Chapter 2.3.

2.1.4 ADVANTAGES AND DISADVANTAGES OF APS TECHNOLOGY

Attractiveness of implementing the technology:

1. APS is compatible with all types of road surfaces and can be extended relatively easily along existing rail, making it suitable for retrofitting.
2. It offers safety benefits where other electrification processes would pose safety risks to pedestrians and road users.
3. Advances in shoe collection technology allow greater line energy transfer efficiencies and reliability (up to 99%) relative to other catenary and non-catenary operations.

Risks of implementing the technology:

1. APS tramways experience problems operating in extremely wet environments or on roads with poor drainage.
2. Heavy rains on small urban streets with old storm water systems have posed significant barriers to reliability in cities such as Bordeaux.
3. Technology remains expensive and significant reductions in capital costs not anticipated with further development.

Advantages established by the example of the tram network in Bordeaux:

1. The system has received acclaim for eliminating the need for overhead wires and preserving the aesthetic form of the dense urban center.
2. Safer alternative to conduit power systems as APS track electrification occurs only on track segments directly underneath each tram.

Drawbacks from the example in Bordeaux:

1. The system has faced difficulties on some streets with poor drainage where heavy rains can lead to short-term flooding and severe delays. This led the city to replace roughly 1km of APS tramway on streets with chronic flooding with overhead wires.

2. Maintenance costs greatly exceeded initial estimates leading Bordeaux to spend more on the small portion of APS track than on the rest of the conventional tram network combined. [2]

With its fully exposed conductor rails, icing is certain to occur. There are some potential solutions, such as electrical trace heating, but they will add cost, both in initial installation and energy wise.

Adapting INNORAIL for use on LRT systems looks possible from a cost, safety, and engineering point of view as long as snow and ice are not a major factor. [7]

2.1.5 CAPITAL COSTS

The average cost for the implenentation of past eleven French systems is € 24m / km, in the range of € 16.9m - € 42.4m.

Stage One of constructing Bordeaux's APS system consisted of three routes totaling 24.5 km and 53 stations that coil through the downtown and close in suburbs of Bordeaux. The Stage 1 system is served by 44 Alstom-built low floor trams. Stage 1 investment was estimated to be around 690 million euros. Taking into account the average price of the Citadis 302 and 402 model vehicles of 3.2 million euros

per vehicle, the estimate of the total cost of the fleet amountes to 140 million for Stage 1, which means that the investment for infrastructure construction amountes to 550 million euros or 22.45 million euros per km of the track.

About 10.5 km of Stage 1 track (or 44%) is equipped with APS. Trams draw power from a surface third rail located in the center of the trackway that is controlled electronically to be activate (energized) only when a collector extending from beneath the tram passes overhead. [6]

Financing in France is reflective of that country’s inclusive multimodal approach to finding long-term solutions to current mobility, congestion, air pollution, and land use dysfunctionalities. Substantial national government financing is available and localities have a number of financing alternatives from which to choose. National, provincial, and localities are expected to contribute to the project, consistent with the benefits received. [6]

2.1.6 **RESULTS OF IMPLEMENTATIO**

The tramway system has been a success since the opening of the three lines. The users of the tram now represents 53% of the public transportation of Bordeaux and the surrounding area. In 2008, 90.3 million passengers had used public transportation with 54.7 millions using the tramway. This represents an increase of 13.4% since 2007.

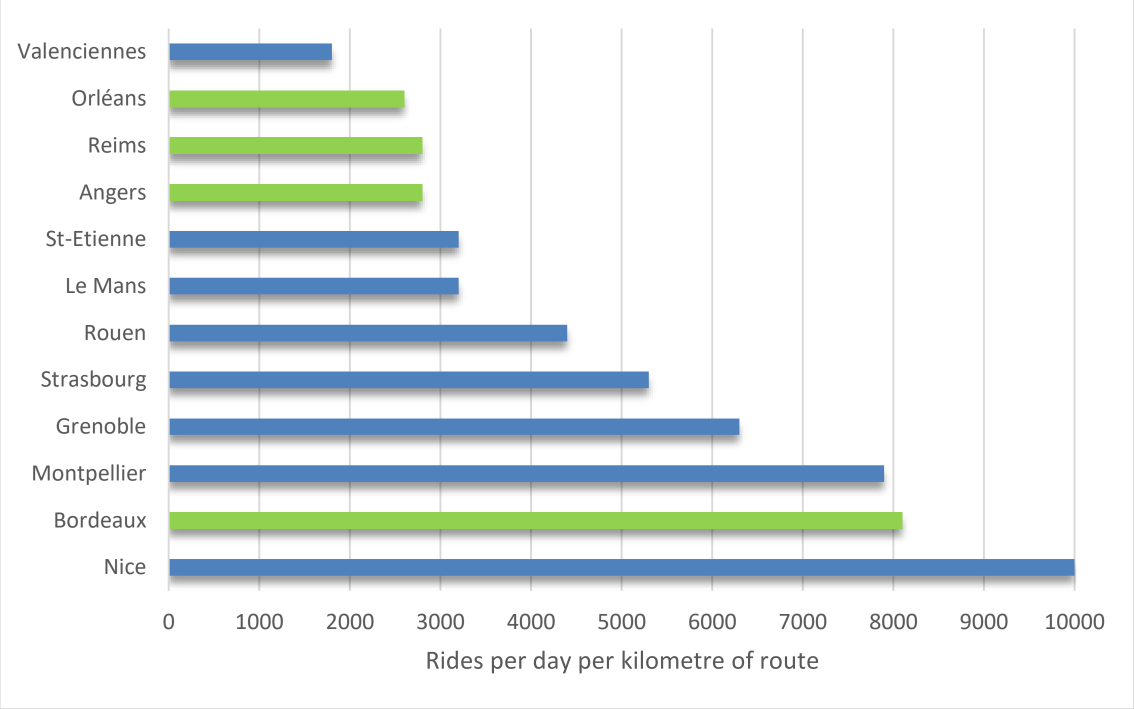

Diagram 1 Results in rides per day per kilometre of route in France, 2010.

Source: [3]

Diagram 1 shows rides per day per kilometer of route in part of French cities that have a tram network. Green labeled cities are using APS technology, it is apparent that Bordeaux is one of the leaders in the number of conducted rides per kilometre, while the largest number of rides is realized by Nice, which will be described in more detail throughout chapter 2.3.2, because Nice also implemented a catenary-free technology in the form of a battery system.

Buses and trams in France are closely integrated with free transfers. Ridership increase is typically 30–60% after a tram network implementation in a city. Montpellier went from 28.8 million passengers per year on the all bus system in 1999, to 62.2m in 2010 with 5 routes, an 150% increase in ridership. [3]

2.2 INDUCTION TRAMS (PRIMOVE)

Coined commercially as “PRIMOVE”, induction powered trams are a novel hybrid technology developed by Bombardier through advances in other catenary-free technologies; namely Alimentation Par le Sol and battery-hybrid trams. The key distinctive of induction powered systems are the use of circuit coils imbedded underground to transfer electromagnetic energy to trams. This contact-free method boasts many of the benefits of APS systems such as wireless tramways, reduced maintenance costs, and safe third-rails. [10]

The modular design of the PRIMOVE system enables a quick and easy installation on both new and existing lines. In addition, the system’s easy installation also allows adaptation to different topographical conditions, operational requirements and distances. [12]

While the technology is significantly more expensive to install and operate than overhead wires, potential advances in battery capacity and transfer efficiency coupled with a catenary-free network makes induction powered tramways an attractive option for heritage districts and city centres looking to minimise visible “wire pollution“. [10]

2.2.1 TECHNOLOGY

Induction powered trams operate through a third-rail system that utilises electromagnetic waves to transfer power between circuit coils imbedded in the ground and pick-up coils on the underbody of the tram. The pick-up coils then convert this electromagnetic energy into electrical current which charges onboard batteries used to power the tram. Similar to APS technology, only the sections of track currently under the tram are magnetised in order to power the tram. [10]

The PRIMOVE system uses the MITRAC energy saver that stores the energy released each time a vehicle brakes and improves the efficiency of operational energy consumption with the ultracapacitor-based storage unit. The PRIMOVE system also provides energy management control system that integrates energy awareness, efficiency and carbon control into an operator’s business.[8]

The MITRAC Energy Saver is based on the series connection of high performance EDLCs, which can quickly charge and discharge high power from train braking and acceleration. When the vehicle is breaking, some of the regenerative energy is stored by the MITRAC Energy Saver and then for train acceleration this energy is distributed to support the power supply, this is one cycle of the MITRAC Energy Saver. The MITRAC Energy Saver is a product developed mainly for energy savings, power supply optimisation and reducing infrastructure investment, running free catenary and performance boosting. Firstly, MITRAC Energy Saver was installed onboard a prototype of a light rail vehicle (LRV) for public transport by the German operator Rhein-Neckar-Verkehr Gmbh in Mannheim, Germany from September 2003 to 2008. The measured performance showed that MITRAC could reduce the consumption of the traction energy by 30%. [9]

Induction powered tram tracks are capable of producing between 200 and 300 kilowatt hours (kWh) of continuous output, which is able to power a roughly 30 metre long light rail vehicle operating at up to 40km/h on a maximum 6% gradient. Commercial applications of up to 500kWh currents are being developed and are anticipated to be able to power carriages up to 42 metres long. [10]

As no direct contact is required for power transfer, the design of the PRIMOVE system is fully flexible and can be customised to the individual needs of any city and customer:

1. Operation is possible over distances of varying lengths and in all surroundings.
2. Reliable performance is ensured, even under adverse weather and ground conditions such as snow, rain, ice, sand or water.
3. Track and wayside components can be completely covered by any ground surface to blend in with their surroundings and to allow for normal traffic flow over the track area.
4. Less land take is needed than for catenary systems as all wayside components fit completely in the envelope of the vehicle and no additional foundation is required. [12]

2.2.2 AUGSBURG, GERMANY PRIMOVE TRAM NETWORK

In September 2010, Bombardier Transportation installed the PRIMOVE contact and catenary-free tram system on an 800-meter section of Line 3 to the Augsburg Exhibition Center. The project was funded by the Federal Ministry of Transport and Digital Infrastructure (BMVI) and realized in cooperation with Stadtwerke Augsburg Verkehrs GmbH. The aim of the pilot project was to demonstrate reliable operation in the city - under real conditions and in daily use. [5]

For testing in a real environment of a tram operation, the route from line 3 of Stadtwerke Augsburg Verkehrs GmbH (STAWA) to the fair in Augsburg was suitable as a test track. By field testing of the vehicle and track components of the inductive power transmission, an optimization of the vehicle technology, the PRIMOVE components, the operating characteristics, but also the maintenance requirements are being developed.

The immediate tasks of the pilot plant were development of the components required for inductive energy transfer and performance coverage, conducting electromagnetic, thermal and mechanical tests, adapting the components to the vehicle and the infrastructure for optimum operational efficiency, optimizing the cost of retrofitting existing vehicles or integrating the components for new vehicles, standardization of PRIMOVE on-board components, ensuring that the technology complies with European standards, approval of the PRIMOVE system for public transport, experience in the operation of trams with PRIMOVE system in a tram operation, metrological monitoring of the line usage, generation of standardized driving cycles for trams with PRIMOVE system, derivation of specifications for the later conversion of vehicles with the PRIMOVE system, planning of the deployment technology and infrastructure.

A bidirectional low-floor Bombardier tram was equipped with two PRIMOVE power pick-ups to capture the inductive energy transferred by eight meters of cables installed between the ground and the tracks. The inverters positioned along the line layout are connected to a 750 Vdc power network. Recreating the normal operating conditions in an urban context, the pilot site has demonstrated the excellent reliability of the system in all environmental conditions as well as full compliance with all application codes and standards for electromagnetic compatibility. Recently, the first prototype of the car was also equipped with the PRIMOVE system, to be submitted to a series of performance tests both in road tests in Augsburg and in the new Bomabrdier center of excellence for electric mobility in Mannheim, Germany.

However, it has also been discovered that changing the memory from the initially used Mitrac Energy Saver to a lithium-ion battery can also meet the requirements of operation. At the same time, infrastructure costs can be significantly reduced. This realization and the resulting change in the system led to battery development for rail vehicles within Bombardier. [11]

2.2.3 NANJING, CHINA PRIMOVE LI-ION BATTERY TRAM NETWORK

Nanjing's new trams represent the next generation of tram technology. Based on new high-power PRIMOVE Li-ion battery systems, the trams operate without overhead cables on 90 per cent of the lines. The batteries are charged seamlessly during normal passenger service via the pantograph statically at tram stops and dynamically during acceleration. The PRIMOVE system was implemented on two tram lines in Nanjing, Hexi line and Qilin line with a total length of 17 km. The first line that was put into a passenger operations was the Hexi line in August 2014, to support the Second Summer Youth Olympic Games. After that Qilin line was put into a passenger operations in October 2016, both lines are shown in Figure 7 and their basic information in Table 3. [24]

Figure 7 Hexi and Qilin line, Nanjing

Source: [24]

Table 3 Nanjing tram lines specifications

LINE	LENGTH	STATIONS	ROUTE
HEXI	8 km	13 stops	Olympic Sports Centre - Fishmount Wetlans Park
QILIN	9 km	13 stops	Maquan - Wangwuzhuang

Source: [25]

There are a total of fifteen (15) vehicles on the lines, eight on the Hexi line and seven trams on the Qilin line. For the purpose of tram charging, each line has three positions, two at end stops where the vehicle is charging approximately 10 minutes and one deport for short duration charge up to 45 seconds. All trams are the Bombardier Flexity 2 model with a long life PRIMOVE battery system and Mitrac propulsion and controls equipment as well as the innovative Flexx Urban 3000 bogies.. Each 5-car tram is equipped with two high-power battery systems of 49 kWh each. Optimized in energy and power density, the modular batteries are perfectly suited for the demanding route profiles of Nanjing's new Hexi and Qilin tram lines. Especially, Qilin line features steep sections and an elevated route over a major highway. Service on these challenging lines demonstrates the suitability of PRIMOVE batteries for reliable and efficient catenary-free operation on nearly any tram line across the globe.

It is the first time ever that trams with PRIMOVE traction batteries have entered into revenue service as well as the first time, in general, that Li-ion batteries have been used for catenary-free tram operation. [24]

2.2.4 **ROLLING STOCK**

Both cityes have a fleet of similar vehicles, the Augsburg rolling stock consists of Bidirectional Bombardier low-floor trams, Flexity Outlook model (Figure 8) and the Nanjing's rolling stock of Bombardiers Flexity 2 model (Flexity 2 tram vehicle shown in Figure 9 combines proven features of Flexity trams and add innovation in design and tehnical features). Their technical advantages include an improved carbody concept, with better corrosion protection and an enhanced bogie design, the Bombardier Flexx Urban 3000. The overall vehicle mass is reduced, and the Bombardier Mitrac propulsion technology results in significantly lower energy consumption. Specifications of the Flexity 2 tram in a 32.2 m long and 2.65 m wide option are shown in Table 5. [29]

Figure 8 Flexity Outlook Tram, Augsburg

Source: [27]

Table 4 Bombardier Flexity tram specifications

Manufacturer	Bombardier
Model	Flexity
Type	uni- and bi-directional
Length of vehicle	30,8 / 40 m
Height	3,45 m
Width	2,4 m
Floor height above TOR	
entrance area	295 mm
low-floor area	355 mm
Percentage of low-floor area	100%
Doors	
Electric double-sliding doors	4 / 5 per side

door clearance height	2,020 mm
door clearance width	1,300 mm
Minimum horizontal curve radius	17,25 m
Car weight (empty)	
uni-directional vehicle, 5 modules	37.9 t
uni-directional vehicle, 7 modules	50.1 t
bi-directional vehicle, 5 modules	39.1 t
bi-directional vehicle, 7 modules	51.5 t
Maximum axle load	100 kN (10.04 t)
Buffer load	400 kN (40.15 t)
Normal current supply	600/700 Vdc
Low voltage	24 Vdc
Maximum speed	70 km/h
Medium acceleration (fully loaded) from 0 to 70 km/h	
uni-directional vehicle, 5 modules	0.75 m/s²
uni-directional vehicle, 7 modules	0.67 m/s²
bi-directional vehicle, 5 modules	0.73 m/s²
bi-directional vehicle, 7 modules	0.65 m/s²
Deceleration (2/3 load)	
service brake	1.2 m/s²
emergency brake	2.74 m/s²
Maximum gradient	50‰
Seated passengers / Standing passengers (4 pass./m2)	
uni-directional vehicle, 5 modules	60 / 129
uni-directional vehicle, 7 modules	84 / 164
bi-directional vehicle, 5 modules	52 / 132
bi-directional vehicle, 7 modules	72 / 173

Source: [26]

Flexity 2 tram vehicle shown in Figure 9 combines proven features of Flexity trams and add innovation in design and tehnical features. Their technical advantages include an improved carbody concept, with better corrosion protection and an enhanced bogie design, the Bombardier Flexx Urban 3000. The overall vehicle mass is reduced, and the Bombardier Mitrac propulsion technology results in significantly lower energy consumption. Specifications of the Flexity 2 tram in a 32.2 m long and 2.65 m wide option are shown in Table 5. [29]

Figure 9 Bombardier Flexity 2 Tram, Nanjinjg

Source: [28]

Table 5 Bombardier Flexity 2 tram specifications

Manufacturer	Bombardier
Model	Flexity 2
Type	bi-directional
Length of vehicle	32.2 m
Height	3.42 m
Width	2.65 m
Floor height above TOR vehicle empty, new wheels	 320 mm
Percentage of low-floor area	100%
Doors Electric double-sliding doors door clearance height door clearance width Electric single-sliding doors door clearance height door clearance width	8 2 per side 2,030 mm 1,300 mm 2 per side 2,030 mm 800 mm
Minimum horizontal curve radius (track / depot)	25 m / 20 m
Car weight (empty)	40.9 t
Car weight (loaded) (4 pass./m2)	56.7 t
Maximum axle load (4 pass./m2)	9.6 t

Buffer load	400 kN (40.14 t)
Normal current supply	600 VDC
Low voltage	24 VDC
Maximum speed	70 km/h
Medium acceleration (2/3 load) from 0 … 70 km/h	0.5 m/s^2
Deceleration (2/3 load) service brake emergency brake	 1.2 m/s^2 2.73 m/s^2
Maximum gradient	60 ‰
Seated passengers	74
Standing passengers (4 pass./m2)	148

Source: [29]

2.2.5 ADVANTAGES AND DISADVANTAGES OF INDUCTION TRAMS

Attractiveness of inductive technology implementation:

1. It offers safety benefits where other electrification processes would pose safety risks to pedestrians and road users.
2. Induction powered trams have high reliability and low downtime under extreme weather conditions such as heavy snow, ice, rain, and sand.
3. The induction loop power can also be extended to other modes of transport equipped with induction coils such as buses and cars.
4. Stations can be converted to charging points for trams as needed.
5. Induction loop systems are compatible with any road surface and almost any road topology.
6. Little to no training required for drivers migration to induction loop system operation.
7. Contactless system reduces maintenance and power system replacement costs.
8. Older tram lines can upgrade to induction relatively easily.
9. When used with super-capacitors, tram batteries, and regenerative braking, systems can provide up to 20-30% energy savings over conventional catenary systems.

Disadvantages when implementing inductive tram technology:

1. Electromagnetic interferences aren't totally mitigated by magnetic shielding when active.
2. Loops must be covered by 40mm layer of non-conductive material such as resin, asphalt base, or non-reinforced concrete and this layer is vulnerable to damage by heavy vehicle traffic.
3. High initial capital costs. [10]

The PRIMOVE system is compliant with all applicable codes and standards for electromagnetic compatibility (EMC). It meets existing requirements for magnetic field emissions in public areas – in particular the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) – and does not interfere with other systems nor with electrical appliances such as mobile phones or heart pacemakers.

As all electric devices are fully isolated, the PRIMOVE system does not present any health or safety hazard to passengers. In Augsburg, Bombardier cooperates closely with external assessors including TÜV SÜD to certify the safety of the system. [12]

2.2.6 CAPITAL COST

When implementing and testing the PRIMOVE technology in Augsburg there was already a built infrastructure so the cost of implementation applies only to the upgrade of the conventional rail. The cost was around 7.7 million euros for the track length of 800 m, which would mean that the cost of upgrading the conventional rail is around 9.6 million euros per kilometer. [51]

Data on implementation costs of PRIMOVE technology in Nanjing are not public.

2.2.7 RESULTS OF IMPLEMENTATION

Catenary-free operation eliminates the need for unsightly overhead wires and poles, thereby increasing the attractiveness of the area. Especially for historic city centres, heritage-protected areas or green environments such as parks and gardens, PRIMOVE technology provides the optimum solution for attractive eco-friendly public transport. Creating significant environmental advantages, it even allows the integration of tram systems in areas where the installation of conventional catenary systems would be prohibited or difficult.

An additional benefit of the system is the integration of the energy storage solution, which is mounted on the vehicle roof: Batteries store the energy released each time the vehicle brakes and allow it to be re-used during operation. Applied to light rail vehicles, the system can save up to 30 per cent of energy, thus reducing costs of electricity generation as well as greenhouse gas emissions. The combination of the PRIMOVE system and the energy storage solution provides optimum performance for continuous operation of catenary-free tram and light rail systems. [12]

2.3 TRACTION BATTERY TRAMS (NiMH)

Traction batteries (or electric vehicle batteries; EVBs) are batteries that are used for the primary or secondary propulsion of electric vehicles. While the majority of electric vehicles used in transport are cars and buses advances in traction battery storage capacities and recharge times have generated new potential for their entrance into light-rail systems. The costs of traction batteries has also dropped significantly over the last decade with some sources suggesting that engineering and replacement costs will continue to decline rapidly over the next fifty years. Used in junction with other technologies traction batteries demonstrate operational energy savings of up to 35%, making them extremely competitive with other catenary-free systems. [13]

2.3.1 TECHNOLOGY

Traction battery trams cycle through a number of ‘modes of operation’ along its service route. Prior to its use, the traction battery must be sufficiently charged which is done either during off-service times in rail yards or while in service through catenary charging, induction, or any other method traditionally used to transfer electricity to the tram. [13]

Figure 10 illustrates four steps of driving system with onboard battery-powered driving system in general. When the pantograph is in its up position at stops or stations, the system uses power to charge the batteries from the overhead lines and extra power is used to operate the auxiliaries such as HVAC systems and electric doors. When the pantograph is in its down position during operation at catenary-free sections, the battery bears all power loads of the vehicle. For acceleration or boosting, the batteries supply power to the traction motors and auxiliary equipment. In particular, the battery power is efficiently managed to minimize energy consumption during coasting operation. When the vehicle brakes or decelerates during stopping, the power system charges the battery with regenerative energy released from its traction motors. The powering system in the LRV consists of up/down converter, inverters to control the connected traction motors, static inverter to control auxiliary components including HVAC and doors, and modular battery packs. [8]

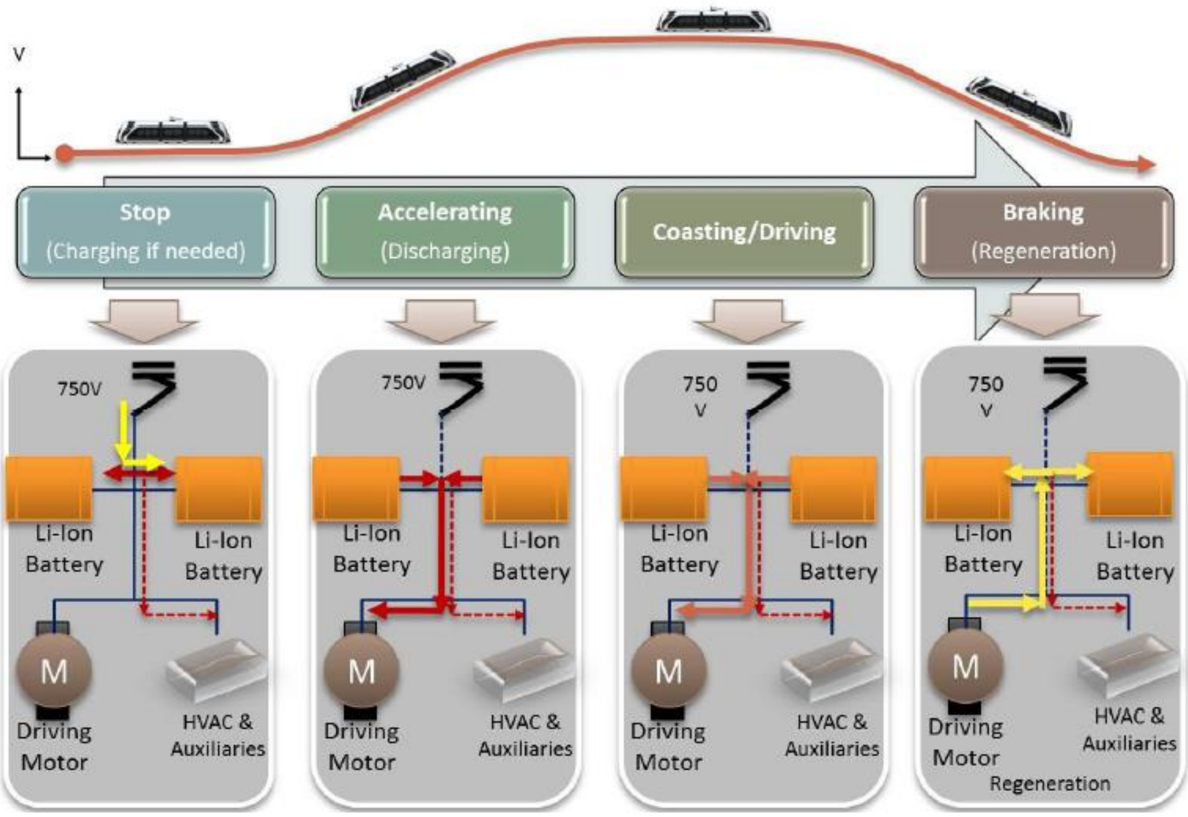

Figure 10 Operational steps of onboard battery-power LRV

Source: [8]

With the very limited energy source from batteries, it is essential to implement efficient energy management system (EMS). The EMS controls energy flows between energy sources, mainly in batteries, and energy loads. Key features of the EMS include:

1. Monitoring battery status, e.g. charging/discharging level, health of batteries.
2. Coasting and coordinating train trip conditions, e.g. boosting/stops and gradient of tracks.
3. Managing auxiliary components consuming energy, e.g. HVAC control, opening/closing doors, indoor lighting controls.
4. Reducing peak power consumption to avoid irregular power breakdown of train
5. Exchanging driving information between driver's control panel and traffic control center.

As a part of energy sources, batteries play a major role as the only energy source in the battery-powered LRV operation. Driving conditions can be systematically changed upon the status of batteries. A Key feature of the battery management system (BMS) is to decide the state of charge (SOC) of batteries which is dependent on voltage, current, resistance, and temperature of battery cells. The BMS works in real time in rapidly changing charging and discharging conditions as the vehicle accelerates and brakes. Thus, the BMS incorporate more vehicle functions than simply managing the battery. It can determine the vehicle's desired operating mode, whether it is accelerating, braking, or stopped, and communicate with the train energy management system. As a part of energy management system, main objectives of the battery management system include

1. Protecting the cells or the battery from damage.
2. Prolonging the battery life
3. Maintaining the battery in a state in which it can fulfill the functional requirements of the LRV operation.

Coupled with the battery management strategies, the vehicle driving control method for the batterypowered train was developed to ensure the operation of the vehicle delivered high energy efficiency and also maximized driving distance. The control method adopted is shown in Figure 10. [8]

2.3.2 NICE, FRANCE NiMH BATTERY TRAM SYSTEM

France's fifth largest city, Nice (350,000), has reacted to a worsening traffic problem by adopting a public transport on reservation (Transport en Commune en Site Propre-TCSP) solution. For Nice, this translates into a modern light rail system as well as an east-west reserved bus line. The light rail system initially consist of an 8.7 km U-shaped line serving the northeast and northern reaches of the city via central Nice, constructed in 2007 is visualized below in Figure 11. [6]

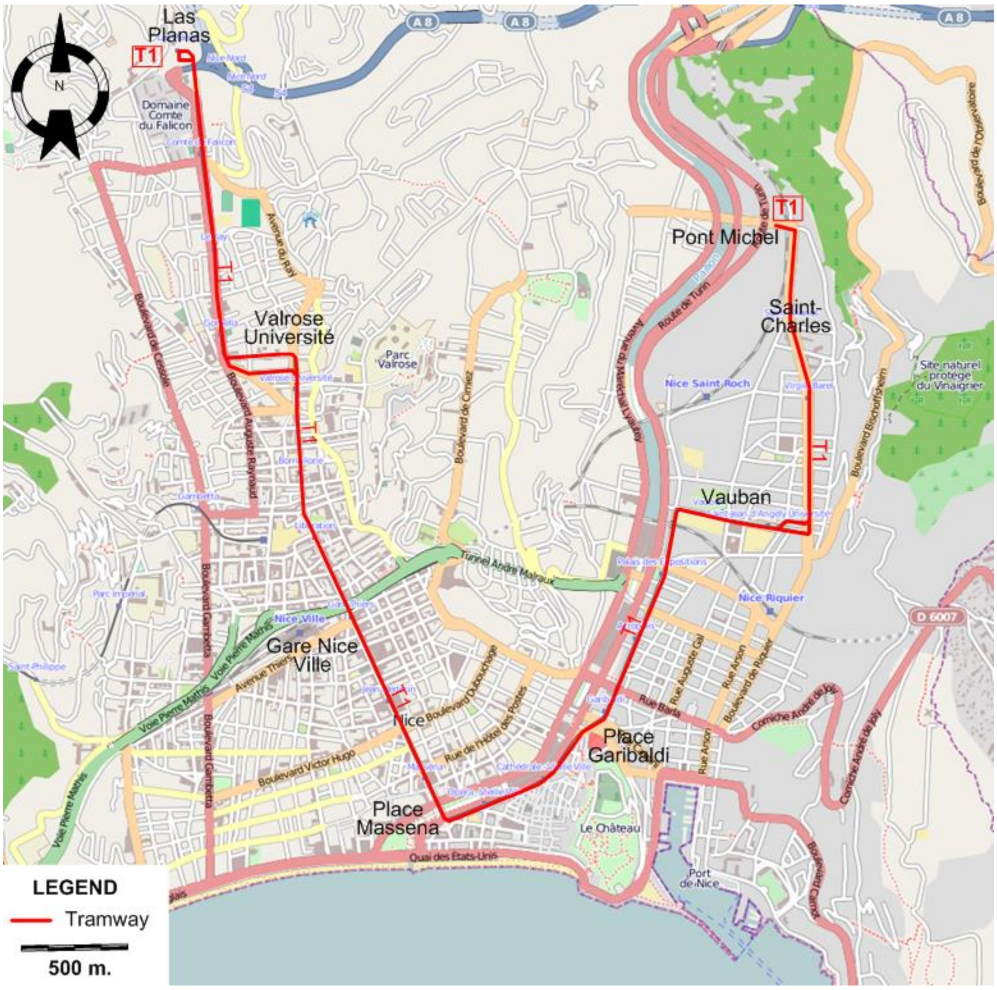

Figure 11 U-shaped line A in Nice

Source: [16]

Following the successful implementation of technology on the first line of public transport, the network has expanded for another 11.3 km long line connecting the city center with the airport and the Central Business District of the city. Service from CADAM to Magnan is planned to start operating in June 2018, service to the airport and Jean Médecin station is planned for late 2018, and service on the complete line is planned for summer 2019. [13]

Table 6 Nice tram lines specifications

LINE	LENGHT	STATIONS	ROUTE
A	8.7 km	21 stops	Henri Sappia - Pont Michel
B	11.3 km with 3.2 km underground	20 stops	Connecting city centre with airport and Central Business District (CADAM, Arénas)

Source: [13]

The lines were constructed using a standard gouge track type of 1435 mm.

A third line shown in Figure 12, expected to be in service by the end of 2019, will run up the Var river valley and connect the Airport to Arénas, Saint-Augustin, the Allianz Riviera Stadium and the quartier Saint-Isidore. Line 3 will consist of 11 stops, five of them crossing over with Line 2 and six new ones. [14] The line will be 7 km long and it is expected to generate 12,000 new passengers per day. The expected budget for building a third line is € 56 million. [15]

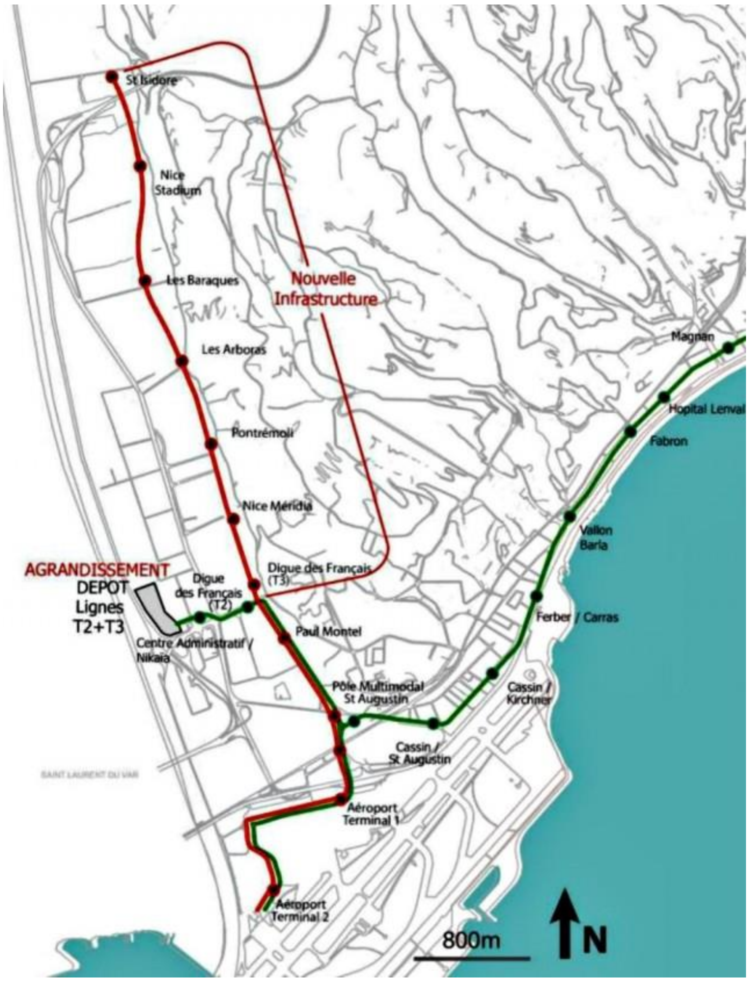

Figure 12 Planned expansion of the tram network in Nice

Source: [15]

Nice even developed a *Plan Lumière* to ensure proper illumination of the street, the tram, and the urban surroundings all along the route. There are eight types of lighting, designed and deployed to accentuate particular urban settings such as historic, cultural or work destinations. In conjunction with the coming of the tram, numerous streets became tram only or auto-free pedestrian zones. The bus system is extensively revised to feed into the tram line. [6]

The Citadis tramway, with an Ni-MH battery, was chosen to operate for the first time in Nice, France, by Alstom transportation. This tram has a maximum speed of 30 km/h and is able to run catenary free over a length of 1 km [6]. Catenary free running was required in two historic squares, the Place Massena and Place Garibaldi, for a distance of about 500 m in each location.

Twenty Citadis vehicles with Ni-MH batteries onboard were sent to service passengers and run without contact wire in these areas at low speed. [9]

2.3.3 ROLLING STOCK

Nice car park consists predominantly of the Alstrom Citadis 302 vehicles that were previously covered in chapter 2.1.3. However, there is a new vehicle order that will also be equipped with a traction battery system. It is also the Alstom brand, model Citadis X05 which is shown in Figure 13 and the vehicle details can be seen in Table 7.

Figure 13 Alstom Citadis X05

Source: [30]

Table 7 Alstom Citadis X05 tram specifications

Type	Citadis 205	Citadis 305	Citadis 405
Vehicle length	24 m	32 m to 37 m	43 m to 45 m
Vehicle width	2.4 m	2.4 m and 2.65 m	2.4 m and 2.65 m
Track gauge	1435 mm	1435 mm	1435 mm
Low floor percentage	100%	100%	100%
Access height	intermediate doors: 326 mm, front doors: 342 mm		
Passenger capacity (4 pass. / m²)			
Seated	41	42 to 66	57 to 82
Standing	101	152 to 184	215 to 237
Total	142	202 to 238	271 to 341
Maximum speed in service	70 km/h	80 km/h	80 km/h
Maximum acceleration	1.3 m/s²	1.3 m/s²	1.3 m/s²
Service deceleration	1.2 m/s²	1.2 m/s²	1.2 m/s²
Minimum horizontal curve radius	20 m	20 m	20 m
Power supply voltage	750 Vdc (600 Vdc as an option)		

Source: [25]

2.3.4 ADVANTAGES AND DISADVANTAGES OF BATTERY SYSTEMS

Advantages of the battery tram system:

1. Offers greater operational range than super-capacitors.
2. Significantly cheaper than super-capacitors.
3. Does not use fossil fuels and improves air quality along lines.
4. Does not require expensive third rail technologies such as electrified ground rails.
5. Safer than third rail electric power transfer.
6. Able to reduce long-term catenary maintenance costs significantly thanks to the recent battery technology improvements.

Drawbacks of implementing a battery system:

1. Longer recharge times compared to other forms of on-board storage such as super-capacitors and fuels.
2. Higher initial purchase price for rolling stock.
3. Often requires regular unit replacement due to short life cycles.
4. Funding sources are relatively poor for battery-only trams worldwide. [13]

2.3.5 CAPITAL COST

Total cost of Nice tram line project was approximately 560 million euros, of which just over 70% related to creating the tramway. Areas of expenditure indicative of the demands of the setting included storm water drainage works (25 million euros), rebuilding of Place Massena (13 million euros), public lighting (4 million euros) and tree planting (1 million euros). [43]

The length of the tram line constructed in that stage was 8.7 km, which would mean that the cost of the infrastructure was around 38 million euros per kilometer. [6] [43]

The cost of purchasing 20 Alstom Citadis type 302 trams amounted to 57 million euros, or 2.85 million euros per vehicle. Roof-mounted Ni-MH (nickel-metal hydride) traction batteries with an operational life of at least five years were supplied by Saft under a €2m contract. Giving trams a range of up to 1km at a maximum speed of 30km/h with air-conditioning in operation, the switching of power being either from the overhead line or the batteries is activated by the driver, with the pantograph fully lowered when running. [43]

Also a new order of Alstom Citadis type X05 trams was made that should enter into commercial service in late 2019. 23 vehicles were ordered at a price of 52 million euros, which would mean that the agreed fare per vehicle was around 2.3 million euros. [52]

2.3.6 RESULTS OF IMPLEMENTATION

While traction batteries have not had a successful history of operation recent technological advances in battery composition and efficiency have allowed these systems to become competitive both financially and energetically with other technologies. Currently there are at least three tram networks using traction battery trams in regular operation in France, Japan, and the US with another at least half dozen cities around the world conducting feasibility studies into their use. [13]

2.4 SUPER-CAPACITOR HYBRID TRAMS

Super-capacitors and super-capacitor/battery hybrid trams are a relatively new addition to catenary-free tram technologies. These trams have evolved from battery-powered or -assisted trams as an alternative method of energy storage and capture. Generally, super-capacitor trams have short operational ranges and charge quickly at stations or rest points. Most super-capacitor systems are paired with traction batteries to provide both high outputs during acceleration and to extend ranges during regular operation and cruising. Bombardier, Siemens, and CAF are all currently developing and offering supercapacitor/battery hybrid trams with varying systems. Chinese light rail manufacturer CSR has also developed a solely super-capacitor tram at its facilities in Guangzhou with plans to enter operation before 2020. [17]

2.4.1 **TECHNOLOGY**

Super-capacitors have much lower energy capacities compared to batteries but offer greater charge densities. These densities can be 10 to 100 times greater than those of batteries and offer significant output during acceleration or climbing gradients and are achieved through the ‘physical rather than chemical’ storage of the energy. The structure of super-capacitors, manely the method by which they store their charge, allows them to be charged and discharged over 100,000 times - far exceeding the number of cycles capable by traditional batteries which average 2,000 to 40,000 cycles. Super-capacitors are also able to capture power from braking sections of track through regenerative breaking, providing further charging and power generation capacities. [17]

The new HES device is the Sitras HES which consists of a nickel metal hydride battery and a Sitras MES (mobile energy storage) module based on EDLCs. The idea behind this hybrid device is the integration of both EDLCs and batteries to obtain the same time high power and energy densities. The device has apparently better performances than the previous energy storage devices, especially for energy saving and running catenary free. The Sitras MES, having energy capacity between 1 and 2 kWh, can be charged quickly and then release the energy stored to the traction motors for the acceleration. On the other hand, a 18 kWh traction battery with high energy density is used to supply the tram for long distances between stations and power to air conditioning and heating required. The HES device is capable of recharging energy from regenerative braking and also from a dedicated quick charging unit at the substations. [8]

With the exception of the Guangzhou super-capacitor-only tram, all trams using the technology to date are super-capacitor/battery hybrids. The batteries help provide power through maintaining speeds on level segments of track while the super-capacitors help provide additional high-current power during acceleration and climbing gradients. These trams average top operational speeds of anywhere between 45 to 70 km/h and average catenary-free operational distances of between 800 m and 2.5 km before recharging. There is a number of super-capacitor-enabled systems available on market with CAF's 'Rapid Charge Accumulator' (ACR), Bombardier's 'Mitrac Energy Saver' (MES), and Siemens' 'Hybrid Energy Storage' (HES) the most popular. [17]

2.4.2 ALMADA, PORTUGAL HYBRID ELECTRIC STORAGE TRAM SYSTEM

The need to increase mobility of passengers in Almada municipality and the emergence of transport sustainability led to the development of a light railway system in the region. The main idea was to integrate road transport, waterway transport, rail and soft modes in the city. Therefore, the Metro Sul do Tejo, a light rail system, was implemented in Almada municipality, south of Lisbon, in Portugal.

This system interconnects the communities of Almada and Seixal, offering connections to the main railway line and ferries serving Lisbon. The system is constituted of 3 track lines shown in and visualized in , ensuring connections between different modes of transport. This light rail has the capacity to transport 300 persons and operates at a maximum speed of 70 km/h. [19]

Table 8 Almada light rail line specifications

LINE	LENGHT	STATIONS	ROUTE
1	13.5 km		Cacilhas – Corroios
2			Corroios – Pragal
3			Cacilhad – Universidade

Source: [17]

Figure 14 Almada light rail network

Source: [18]

This network is very important for municipality because it operates in a densely populated area, and connects to main interfaces, rail (Pragal) and waterway (Cacilhas). However, the usage of the line by passengers has been lower than anticipated. From 2008 to 2010, the volume of traffic was 30% below predictions. Even though it offers a capacity of 260000 passengers/day and 6000 on peak time, this service has not been able to fully occupy its place in the chain of transportation and fulfill its potential capacity. [19]

2.4.3 **ROLLING STOCK**

For the purpose of carrying out public transportation in Almada, operate the Siemens Cambino Plus model trams shown in Figure 15. Each end of the car is equipped with driver’s cabs to enable bi-directional operation. Each vehicle comprises four sections (or modules) of the same length and features four bogies, three of which are powered. The bogies are arranged in the centre of each module. The tram is equipped with a passive hydraulic ride stabilization systems, each linking two modules. This system improves the ride quality of the vehicle and ensures an optimum envelope under all operating conditions. [31]

Figure 15 Siemens Cambino Plus, Almada

Source: [32]

The electrical equipment is concentrated in containers which are integrated into the roof structure of the car body. Three modern Integrated Gate Bipolar Transistor (IGBT) pulse-width-modulated inverters, low-wear three-phase asynchronous motors and a 32-bit traction control unit (Sibas 32) are used as traction equipment. The traction system also allows power recovery. The vehicle's control equipment is based on a vehicle data bus system backed up by wired control lines for essential train control functions.

For the auxiliary and secondary equipment, low-wear and low-maintenance components are used throughout the vehicle. The Combino Plus features four separate and independent brake systems:

1. electrodynamic brake on powered running gear
2. hydraulically passive spring-loaded brake on powered running gear
3. hydraulically active disk brake on non-powered running gear
4. electromagnetic track brake on all running gears

Design and brake performance conforms to the German standard BOStrab. Basic vehicle details are shown in Table 9. [31]

Table 9 Siemens Cambino Plus tram specifications

Manufacturer	Siemens
Model	Cambino
Type	Four-section, 100 % low-floor articulated, power car for bi-directional operation
Traction adhesion	75%
Wheel arrangement	Bo‘Bo‘2‘Bo
Length of vehicle	36,360 mm
Height	3,616 mm
Width	2,650 mm
Maximum axle load	<10 t
Vehicle capacity	232
seated passengers	74 + 4 folding seats
standing passengers (4 pers./m²)	154
Maximum speed (design speed)	70 km/h
Max. speed (operational)	60 km/h
Max. Starting acceleration	1.3 m/s
Mean service deceleration	1.1 m/s
Number of doors	5 double doors per side
Line voltage	(750 V DC) +20% / -30% via overhead contact wire
Traction motors (normal operating point)	6 x 100 kW
Wheel diameter new / worn	600 mm / 520 mm
Low-floor percentage	100%

Floor height	350 mm
Entrance height	320 mm

Source: [31]

2.4.4 ADVANTAGES AND DISADVANTAGES OF SUPER-CAPACITOR HYBRID TRAMS

Attractiveness of super-capacitor hybrid tram systems:

1. Offers greater energy densities and outputs than traction batteries.
2. Significantly greater number of life cycles than traction batteries.
3. Extremely short recharge times of 10-30 seconds, allowing for near-full recharges at stations.
4. Does not use fossil fuels and improves air quality along lines.
5. Does not require expensive third rail technologies such as electrified ground rails.
6. Can be installed on tradition tram carriages and integrated into propulsion systems.
7. Technology is supported and in development by many high-end engineering companies, promising significant improvements and upgrades in the next decade. [17]

Disadvantages of hybrid tram systems:

1. Currently one of the most expensive tram technologies.
2. Very low energy capacities, generally requiring auxiliary or assistant systems to fully operate catenary-free.
3. High maintenance and replacement costs, although greater life expectancy than traction batteries.

2.4.5 CAPITAL COST

At the moment there are not data available on the costs of implementing super-capacitor hybrid system trams.

2.4.6 RESULTS OF IMPLEMENTATION

In November 2008, the Sitras HES was installed on the roof of a redesigned tram belonging to the Portuguese company Metro Transports do Sul S.A. (MTS), called ‘Combino plus MTS’, which serviced passengers between Almada and Seixal in the south of Lisbon. The in service operation for passengers with the application of the Sitras HES on the Combino plus MTS was certified and evaluated by the TÜV Süd GmbH according to the German Federal Regulations on the construction and operation of light rail transit systems (BOStrab) in terms of risk analysis, operation and protection concepts. This had the effect of reducing the CO2 emissions by 80 metric tons per year. The typical catenary free length of the trams equipped with Sitras HES was approximately 2.5 km. In critical situations such as power outage of the train because of a failure of the pantograph or a fault within the substation or for short periods of maintenance works on the traction power supply, onboard traction batteries were able to power the tram over the next station. [8]

Generally, batteries are characterised by high energy density, so they can store plenty of energy and support their load more than EDLCs and flywheels; however, they present recharge time higher than those of the EDLCs and flywheels. Another disadvantage of batteries is that they have a number of life cycles approximately equal to one hundredth of those of the EDLCs and flywheels. The combination of batteries and EDLCs or flywheels, called ‘Hybrid Energy Storage Device’, has a better performance in comparison with the single energy storage device. [9]

3 ANALYSIS OF THE EXISTING PUBLIC TRANSPORT NETWORK IN WIESBADEN

Large cities like Wiesbaden often have a public transport system, in which a tram or metropolitan railway network with linear development is able to handle most of the urban public transport demand, supplemented by a bus network for area coverage (eg Mainz, Karlsruhe, Freiburg, Kassel, Darmstadt etc.). This is not the case in Wiesbaden, bus transport in the urban area takes over both the linear and the area-wide development. [35]

3.1 POPULATION

According to the data collected in 2013 from the city of Wiesbaden and the Rheingau-Taunus district, the inhabitants in the two task-bearer areas are distributed as follows:

1. State capital Wiesbaden (regional center): 279,564
2. Rheingau-Taunus district: 183,179.

According to these date it can be concluded that around 463,000 people live in these two task-bearer areas. For the 26 districts in Wiesbaden the distribution for year 2013 is shown in Table 10. [33]

Table 10 Population distribution in Wiesbaden

Local districts	Population
Auringen	3.394
Biebrich	37.582
Bierstadt	12.199
Breckenheim	3.374
Delkenheim	5.034
Dotzheim	26.698
Erbenheim	9.597
Frauenstein	2.377
Heßloch	686
Igstadt	2.141
Klarenthal	10.453
Kloppenheim	2.305
Mainz-Amöneburg	1.501

Mainz-Kastel	12.461
Mainz-Kostheim	14.122
Medenbach	2.479
Mitte	21.303
Naurod	4.342
Nordenstadt	7.843
Nordost	22.732
Rambach	2.167
Rheingauviertel, Hollerborn	20.748
Schierstein	10.174
Sonnenberg	8.045
Südost	18.637
Westend, Bleichstraße	17.170
Total Wiesbaden population	**279.564**

Source: [33]

The distribution and population density in Wiesbaden is shown in Figure 16 and Figure 17.

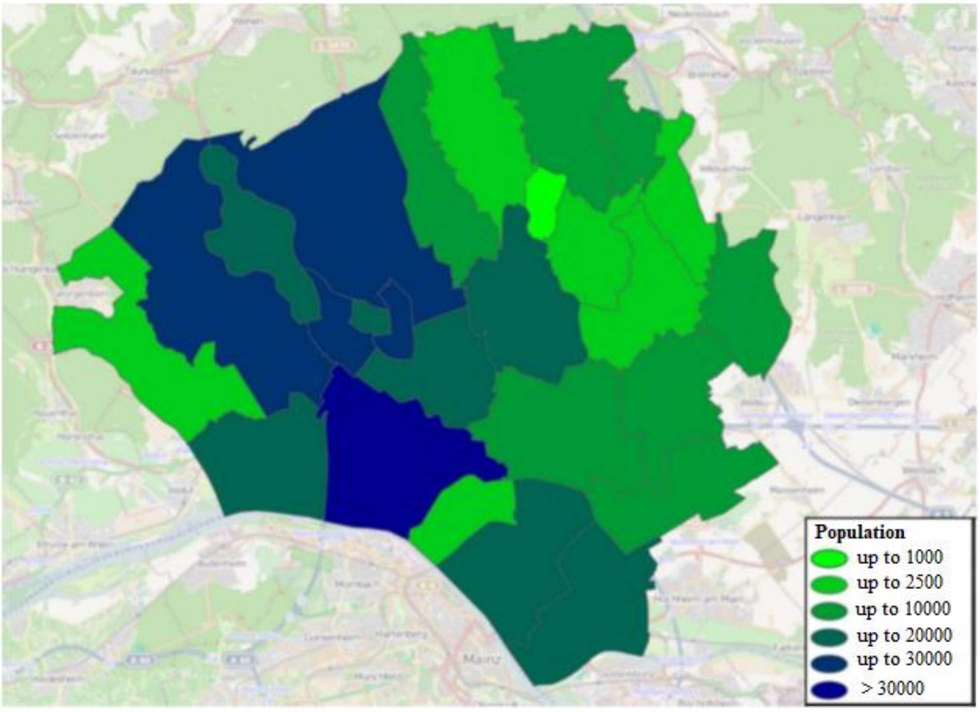

Figure 16 Population distribution at Wiesbaden, 2013

Source: [33]

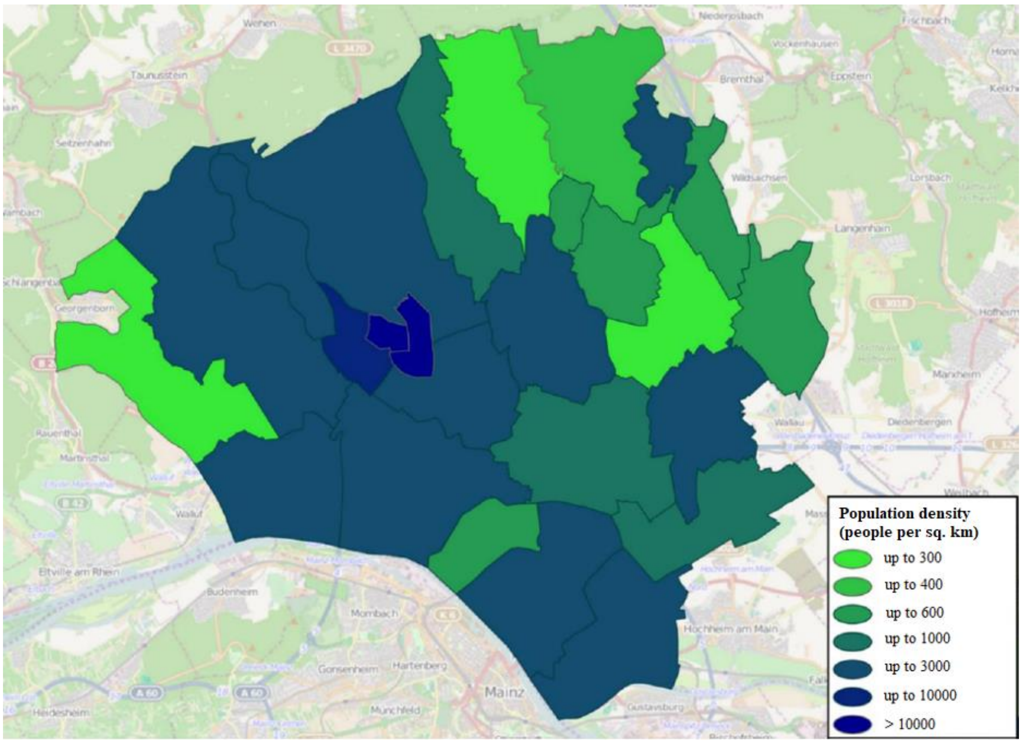

Figure 17 Population density in Wiesbaden, 2013

Source: [33]

As can be seen from the enclosed Figures, Wiesbaden has a large percentage of the population living in the city center and has the highest population density per square kilometer.

By contrast, the northeastern districts predominantly have a lower population density. Of the approximately 183,000 inhabitants in the Rheingau-Taunus district, around 73% live in the centres or subcentres of the region as shown in Table 11.

Table 11 Population distribution in Rheingau-Taunus district

Centres	**Population**
Taunusstein	29.000
Idstein	23.476
Eltville am Rhein	17.713
Geisenheim	11.560
Bad Schwalbach (Kreisstadt)	10.646
Rüdesheim am Rhein	9.659

Subcentres	Population
Niedernhausen	14.431
Oestrich-Winkel	11.583
Aarbergen	5.957

Source: [33]

The distribution and population density in Rheingau-Taunus district is shown in Figure 18 and Figure 19.

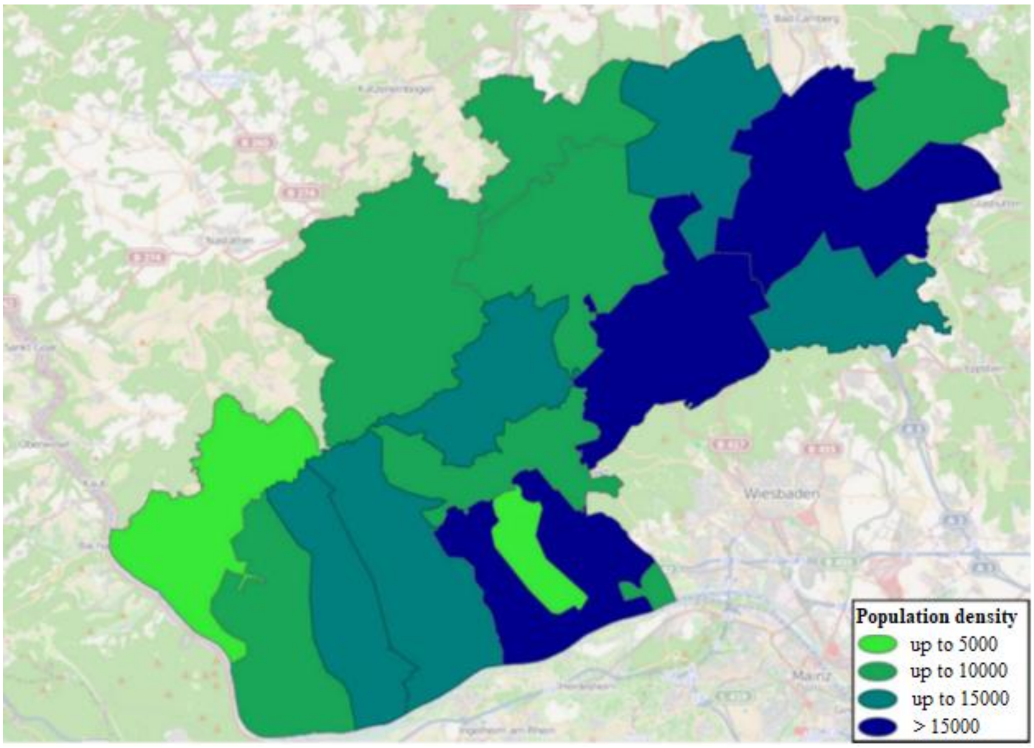

Figure 18 Population distribution in Rheingau-Taunus district, 2013

Source: [33]

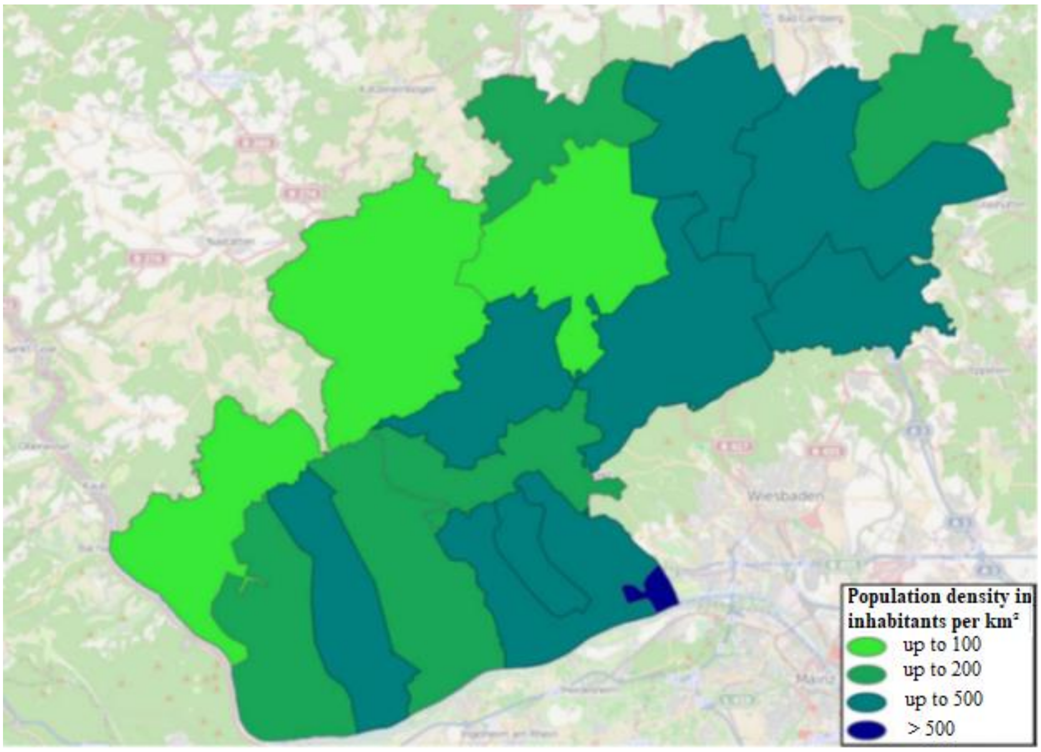

Figure 19 Population density in Rheingau-Taunus-Kreis, 2013

Source: [33]

The highest percentage of the population in the Rheingau-Taunus district, as well as the highest population density, are found in the southern and eastern municipalities. With increasing distance from the upper center of Wiesbaden, the population density decreases.

By 2020, a slight increase in population is expected in Wiesbaden. In the Rheingau-Taunus district, a slight decline in the population of just under 1% is to be expected. Furthermore, it should be noted that demographic change will increase the population, especially in rural areas. [33]

The population development from 2013 to 2020 for the city of Wiesbaden per local district and for the Rheingau-Taunus district per municipality is shown in Figure 20 and Figure 21.

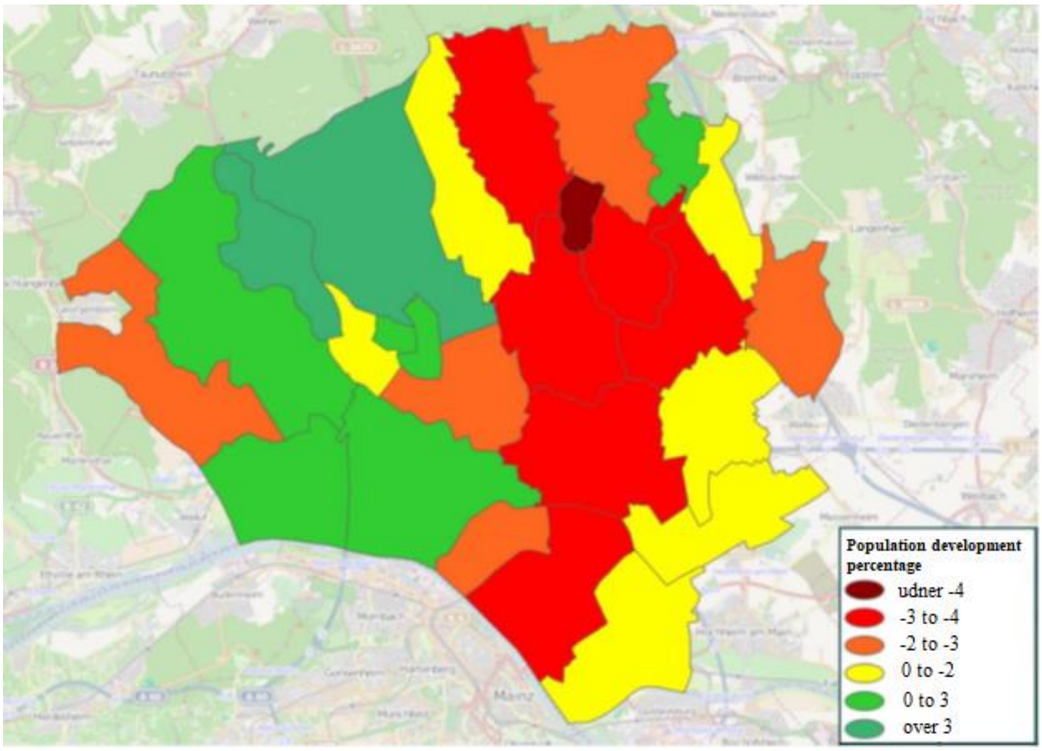

Figure 20 Change in population development from 2013 to 2020 for Wiesbaden

Source: [33]

For the public transport plan of the city of Wiesbaden, the planned new development areas have to be considered within the city area. In particular, attention is drawn to the two new development areas Bierstadt - Nord (in Bierstadt) and Hainweg (in Nordenstadt), which can be expected to generate significant growth for local public transport. [33]

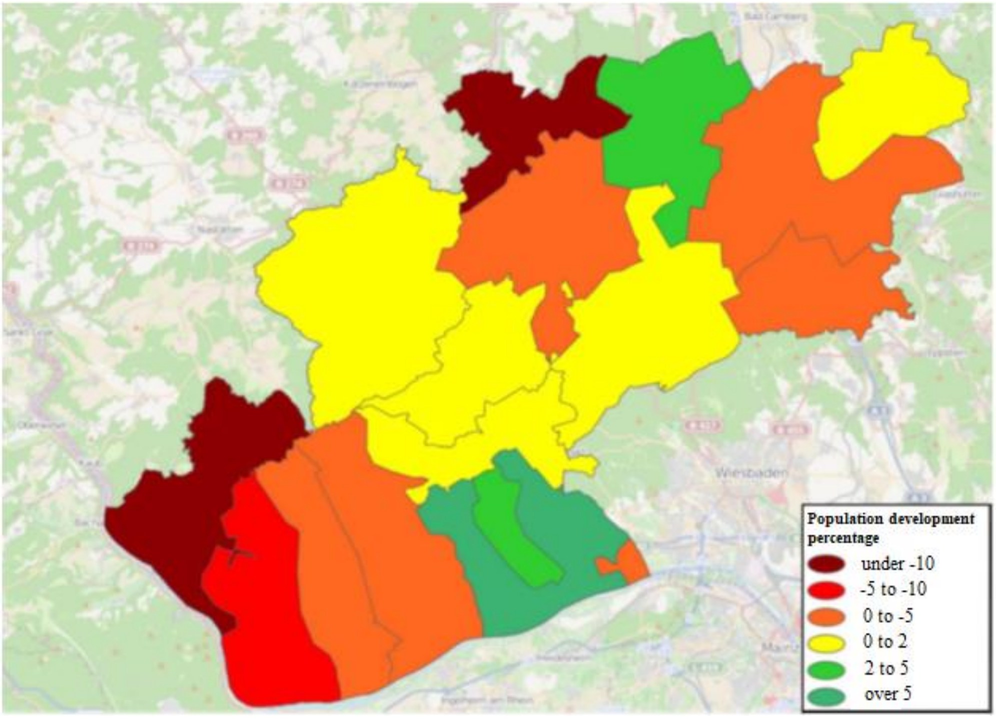

Figure 21 Change in population development from 2013 to 2020 for the Rheingau-Taunus-district

Source: [33]

In the Rheingau-Taunus district, the planned new development areas are covered by public transport., with the exception of a sub-area of the new Taunusstein-Wehen development area. [33]

3.2 TRAFFIC FLOW

In the following segment, the basic traffic flows between the municipalities or districts or traffic cells are described. The demand data comes from the current RMV Survey 2010 and is available in a structure as a source-target matrix separately for adults and students. The local traffic plan also took into account the spaces and traffic flow leaving the task carrier space (e.g., source-destination traffic to Frankfurt).

In total, the traffic model contains 816,500 passengers per working day. They are divided into adults and students as follows:

1. Adults: 670,000
2. Students: 146,500.

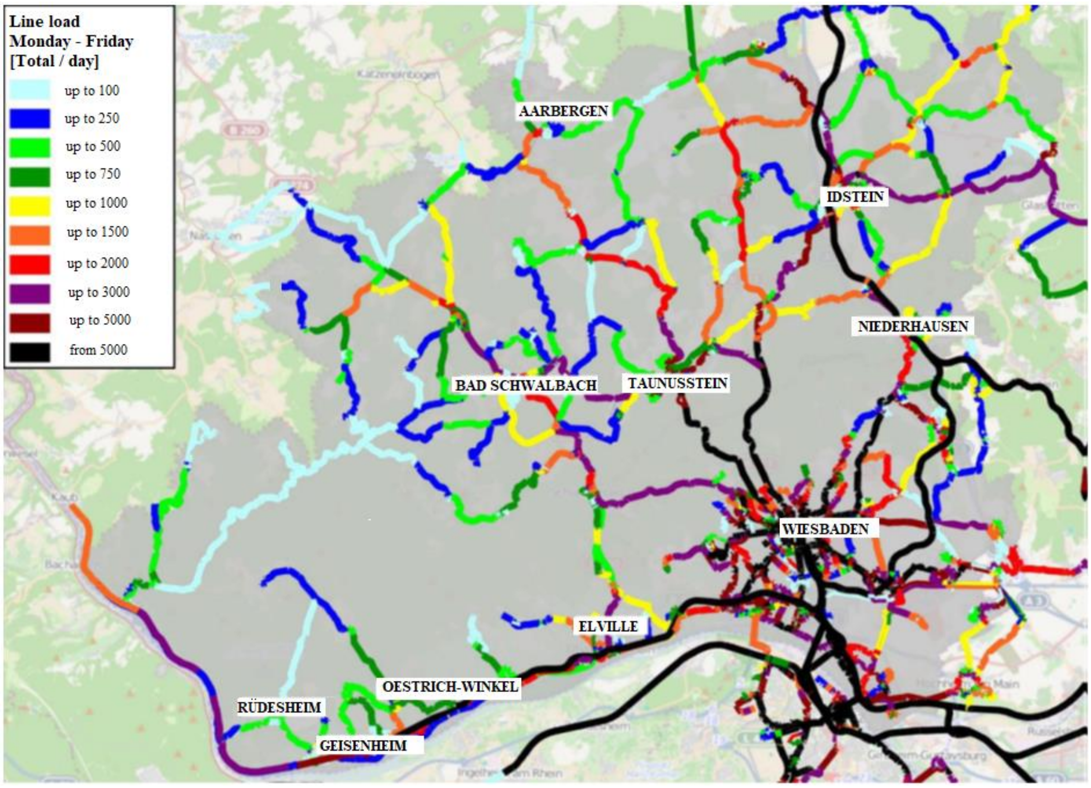

Figure 22 Traffic flow in Wiesbaden, 2010

Source: [33]

The clear orientation of the traffic flows Monday-Friday (MF) to the middle centers and the upper center is shown Figure 22. It can be seen that the demand on the routes used by public transport to the center is increasing.

For the city of Wiesbaden, Figure 23 describes the route loadings per working day in the city center. Focusing on the city center, it can be seen that passenger flow of between 11,000 and 20,000 passengers per day should be expected on daily public transport routes. [33]

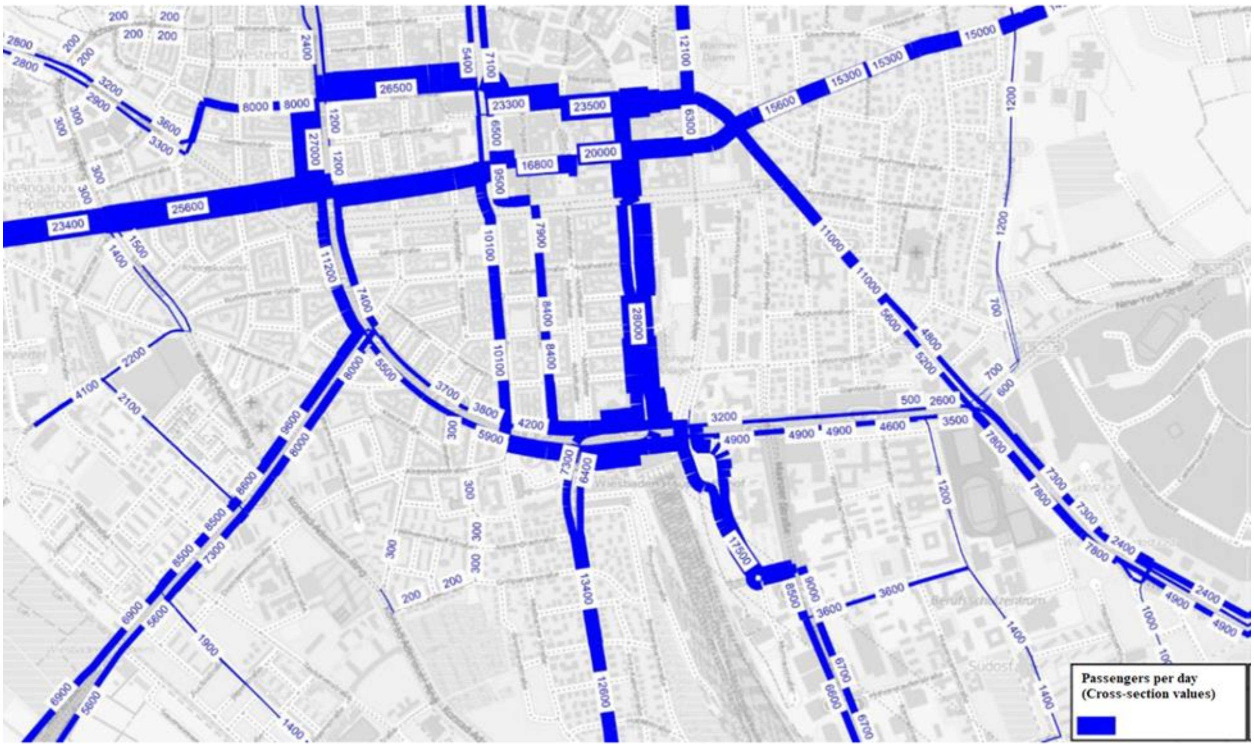

Figure 23 Passenger flows within Wiesbaden (MF) - Excerpt downtown

Source: [33]

Looking at the planned route of the tram line, it can be seen that the loads on these shares range from about 11,000 to 25,000 passengers per business day, while in the narrower center of the city these numbers reach 40,000 passengers per day as shown in Figure 24.

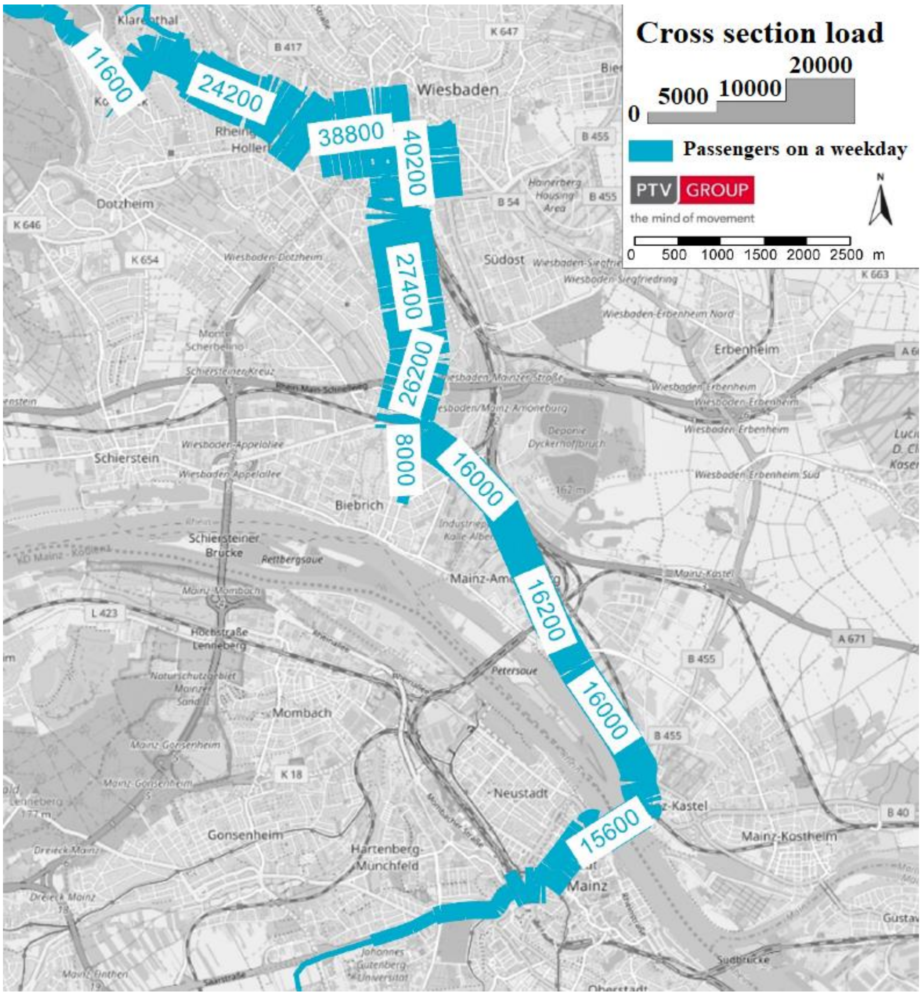

Figure 24 Cross section load on the future route of the tram

Source: [38]

3.3 BUS TRANSPORT

The basis for the urban line network is the original network concept from the year 1969. After that, all lines were routed in or through the city.

Starting from the outside, the lines are tied in the city center in a star shape until the first city ring. The strong bundling of sections of parallel lines leads to dense wagon sequences over long distances.

Today, the range of local bus services offered is predominantly provided by ESWE Verkehrsgesellschaft mbH. ESWE currently has 41 line concessions for public transport in the state capital Wiesbaden, including seven joint licenses with the Mainzer Verkehrsgesellschaft (MVG) (lines 6, 9, 28, 33, 45, 47 and N7). The Community Line 68 of the MVG and the Omnibusverkehr Rhein Nahe GmbH (ORN) also operates, as the previously named lines, between Mainz and Wiesbaden.

There are also other bus operator companies in the Wiesbaden area, mainly used for connecting the neighboring districts to Wiesbaden. From the Rheingau-Taunus district these are the lines 170, 171, 200, 225, 245, 270, 271, 272, 274, 275. From the Main-Taunus district it is the line 262. These bus lines represent the bus-side connection between the surrounding areas and Wiesbaden, which is to remain intact in the future. The two main destinations of these bus lines in Wiesbaden are the city center and the main train station. [33]

General information about bus lines in Wiesbaden are visible in Table 12 and and their visualization is shown in the Figure 25 and it is indicated which of the public transport operators corresponds to the appropriate one.

Table 12 Overview of the Wiesbaden bus lines

Line	**Route**		**Operating hours**	
	from	to	from	to
1	Dürerplatz	Nerotal	4:30	0:30
2	Klarenthal	Sonnenberg	HVZ morning and afternoon	
3	Nordfriedhof	Biebrich	4:40	0:00
4	Kohlheck	Biebrich	4:15	0:20
5	Schierstein	Erbenheim Nord	4:40	0:15
6	Nordfriedhof	Mainz Marienborn	4:00	0:30
8	Steinberger Straße	Eigenheim	4:40	0:20
9	Schierstein	Mainz Isaac-Fulda-Allee	4:50	23:40
14	Carl-von-Linde-Straße	Schierstein	4:30	0:30
15	Gräselberg	Nordenstadt Westring	4:30	0:30
16	Südfriedhof	Rambach	4:30	0:30
17	Klarenthal	Bierstadt Wolfsfeld	5:40	20:40
18	Sauerland	Sonnenberg	5:00	0:30
20	Naurod	Niederjosbach	5:20	19:50
AST 20	Naurod	Niederjosbach	Saturdays 18:00 - 20:00	
21	Platz der Deutschen Einheit	Medenbach	4:40	0:30

22	Berufsschulzentrum	Oberjosbach	5:20	0:15
23	Schiertsein	Breckenheim	4:50	1:00
24	Frauenstein	Heßloch	4:30	0:50
26	Medenbach	Bremthal	HVZ morning and afternoon	
AST 26	Medenbach	Bremthal	single rides a day	
27	Schelmengraben	Freizeitbad	5:50	20:30
28	Platz der Deutschen Einheit	Mainz	5:00	21:30
33	Tierpark Fasanerie	Kostheim	5:00	0:30
34	Platz der Deutschen Einheit	Unterer Zwerchweg	5:15	16:50
37	Wielandstraße	Bierstadt / Erbenheim	4:30	20:30
38	Europaviertel	Biebrich	individual trips to school	
39	Dr.-Horst-Schmidt-Kliniken	Bahnhof Wiesbaden Ost	5:00	0:15
43	Breckenheim	Wiesbaden Hauptbahnhof	6:00	22:20
45	Mainz Hauptbahnhof	Raiffeisenplatz	4:30	21:50
46	Wiesbaden Hbf. / Platz d. Dt. Einheit	Hochheim	5:40	21:00
AST 46	Wallau	Wicker oder Hochheim	6:40	18:30
47	Frauenstein	Gonsenheim	5:30	20:30
48	Nordfriedhof	Hochheim Bahnhof	4:30	0:30
54	Ginsheim	Lerchenberg	4:00	0:10
55	Bischofsheim	Finthen	5:30	21:00
56	Kostheim	Münchfeld	4:50	23:50
57	Kastel	Gonsenheim	4:50	20:50
68	Hochheim	Klein-Winternheim	5:00	1:00
91	Bischofsheim	Fintehn	only night driving	
99	Kastel	Mainz Hauptbahnhof	a night drive	
262	Platz der Deutschen Einheit	Hofheim Bahnhof	5:30	21:00
N 2	Platz der Deutschen Einheit	Delkenheim	only night driving	
N 3	Platz der Deutschen Einheit	Schierstein Oderstraße	only night driving	
N 4	Dernsches Gelände	Frauenstein	only night driving	
N 5	Hauptbahnhof	Kohlheck	only night driving	
N 7	Platz der Deutschen Einheit	Kostheim	only night driving	

N 9	Dernsches Gelände	Schierstein	only night driving
N 10	Schlachthof	Medenbach	only night driving
N 11	Platz der Deutschen Einheit	Breckenheim	only night driving
N 12	Dernsches Gelände	Schierstein Hafen	only night driving

Source: [34]

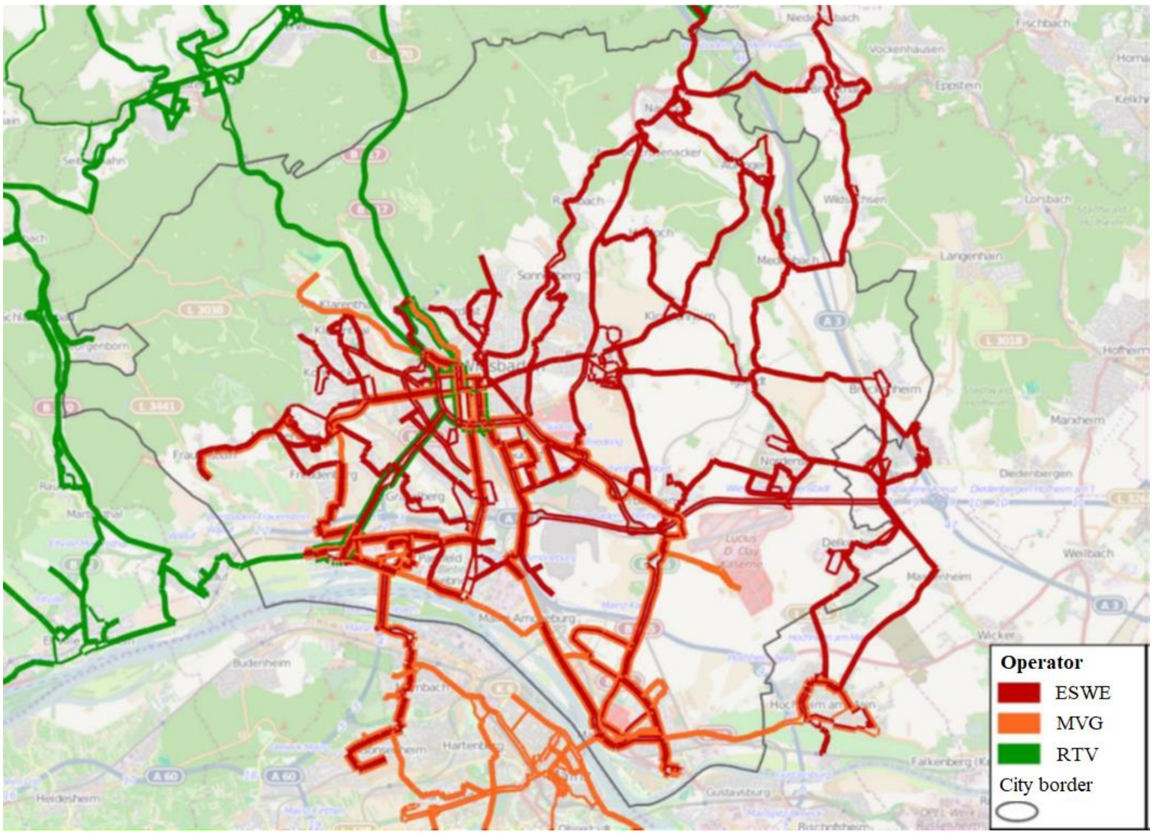

Figure 25 : Wiesbaden bus line network and their operators or transport authorities

Source: [34]

In addition to the radial lines there are few lines with tangential character. These are the lines:

1. Line 9: Schierstein - Biebrich – Mainz
2. Line 37: Wielandstraße - Hauptbahnhof - Bierstadt / Erbenheim
3. Line 38: Europaviertel - Biebricher Allee via the Waldstraße (runs only during school hours)
4. Line 39: Dotzheim - Biebrich Cemetery via Erich-Ollenhauer-Straße.

The regular service is supplemented by three demand-oriented offers; these are:

1. Call collection taxi AST 20: Naurod – Bremthal
2. Call collection taxi AST 26: Medenbach - Wildsachsen – Bremthal
3. Call collection taxi AST 46: Wallau - Massenheim - Wicker or Hochheim.

All three AST lines are commissioned by the Main-Taunus-Verkehrsgesellschaft (MTV).

The main stops with the highest passenger flows are the main train station in the city of Wiesbaden and the stops in the city center:

1. Dernian terrain / Wilhelmstraße
2. Kirchgasse / Luisenplatz
3. Schwalbacher Straße / LuisenForum
4. Place of German Unity
5. Bismarck ring
6. Lorelei ring.

In particular, the main station assumes the function of a transfer point for regional rail traffic and long-distance traffic.

The operating hours of the daily network of local bus lines are between 04:30 and 00:30. In addition, on the nights from Friday to Saturday, Saturday to Sunday and before public holidays in Hesse, night-time services are offered from 00:30 to 04:30.

The average transport speed (timetable) of the lines in daily traffic is just under 19 km / h. The travel offer of the bus lines is switched off all day. The clock offer depends on the minimum standards (30-minute or 60-minute intervals) and the number of passengers (10-minute cycle with amplifier drives). [33]

3.4 REGIONAL RAIL TRANSPORT

The linking of the local bus networks with the adjacent transport authorities and destinations located further away is predominantly via regional rail traffic.

The main link here is the main train station in Wiesbaden. The following lines run from this station:

1. S1: Wiesbaden - Hochheim - Frankfurt - Ober-Roden
2. S8: Wiesbaden - Mainz - Ruesselsheim - Frankfurt - Hanau Hbf.
3. S9: Wiesbaden - Kastel - Rüsselsheim - Frankfurt - Hanau Hbf.
4. RB 21: Wiesbaden - Niedernhausen - Limburg
5. RB 75: Wiesbaden - Mainz - Darmstadt - Aschaffenburg
6. SE 10: Koblenz - Neuwied - Rüdesheim - Wiesbaden – Frankfurt.

In addition to the main train station in Wiesbaden there are seven further stations on the Wiesbaden district where the above mentioned lines also stop.

3.5 CONCLUSION

Overall, Wiesbaden has a well-functioning bus system, which is relatively well accepted by the citizens. Basically, however, the bus system in its current form, at stops and on the routes regularly reaches capacity limits, so that attractiveness and performance of public transport are impaired. [35]

Due to this problem, it is necessary to present the city with a new form of public transport that can meet passenger’s needs. This is mostly aimed at increasing the capacity of public transport, especially in peak hours. In order to achieve this, it is logical to implement a tram network in Wiesbaden, because the current demand meets the conditions for justifying such implementation and according to forecasts, the demand will increase as well as the number of residents in the city area.

4 PROJECT ANALYSIS OF THE FUTURE TRAM NETWORK IN WIESBADEN

The capacity of the road network in the state capital Wiesbaden has reached its limits. Despite already largely utilized measures to improve the quality of the public transport in aspect of supply and infrastructure (e.g. Bus lanes and signal prioritization) restraints for all road users are still noticeable. Due to the predicted structural development in the city an improvement seems unlikely. Facing it, in July 2011 the decision was taken to consider a rail system in addition to today's public transport.

The local public transport in the city of Wiesbaden is currently dominated by a bus bid with a total of 32 lines and making it one of the largest independent bus networks in Germany. The introduction of a new tram system in the city will lead to a comprehensive restructuration of the existing bus concept. The bus will take on the feeder function for the tram system. The integrated traffic concept and avoidance of parallel supply leads to a drop in costly operating service by increasing passenger capacity. [36]

4.1 PLANNED TRAM NETWORK IN WIESBADEN

The marked out route shown in Figure 26 represents the initial concept of the tram network with which planning began. It runs from the north-west via the inner city to the south-east of Wiesbaden and its planned length was about 10 km. The implementation of the project improves the public transport significantly and leads to a major modal shift. According to first estimates around 10,000 more people will use the public transport per day for their travels and the volume of private transport will drop. In this way, an increase in quality of the transport within the city is achieved with a significant reduction of emissions. The remaining bus network is facilitated by the introduction of a rail axis in the major demand corridor of the city. [36]

Figure 26 Initial plan of the tram network in Wiesbaden

Source: [36]

The plan consists of the construction of three tram lines that will cover the city center of Wiesbaden and connect it with the rest of the city and thus increasing the quality of public transport services. In the first phase of the project, a line is drawn up that will link Wiesbaden and Mainz due to the large number of travels between the cities created by the place of residence and workplaces, large number of students living in the area and traveling between those locations and cultural attractions in the city. The first phase of the plan is to connect two major universities, Hochschule Mainz and Hochschule Wiesbaden RheinMain. [36] Around 200,000 people live and work in the catchment area of the CityBahn in Wiesbaden and Mainz, and can reach the stops within a radius of 600 meters. [40]

In the future phase, the extension of the tram network to the Rheingau-Taunus district is also planned, due to the large number of trips on that route.

The expansion of a tram system network with three light rail lines is useful in the sense of the traffic demand. The network effect of this three tram lines is calculated by 25.000 new passengers per day and the positive demand effect in not limited just to the tram corridors, but also expends over the entire city. [36]

The route in detail was separated in to two main parts:

1. Railway station Bad Schwalbach to Mainz University which runs over Aartalstrecke, Simeonhaus, Wiesbaden University of Applied Sciences RheinMain, Dotzheimer Straße / Luisenstraße, Bahnhofstraße, Wiesbaden main station, Biebricher Allee, Kasteler Straße, Theodor-Heuss-Brücke, Grosse Bleiche and from Mainz main station West on the new Mainzelbahn line to Mainz Hochschule.
2. A branch line with the Hermann-Brill-Straße branch (Klarenthal, from Otto-Wels-Straße back on the main line) and in Biebrich with the branch to Rathenauplatz (branch off intersection Kasteler Straße / Straße der Republik). [40]

4.2 FIRST STAGE OF CONSTRUCTION

In the first stage of operation, the CityBahn line 11 will run between Bad Schwalbach and Mainz. The line 11 is intended to form together a connection between the Aartalbahn (railway line connecting Wiesbaden and Rhineland-Palatinate Diez) and the Biebrich district with the line 10 on a 5-minute interval. Between Biebrich and Mainz the line 11 will run every 10 minutes and if necessary can be reinforced by the line 10. There is also the possibility to execute some trips in double traction and to accelerate line 10 as an express line with few selected stops, but such options are still examined in the context of the further capacity checks. [37]

Figure 27 shows the list of train stations and scheduled intervals of the vehicle operating between them. Also shown are the locations where the new line will reach and connect to the existing tram network in Mainz.

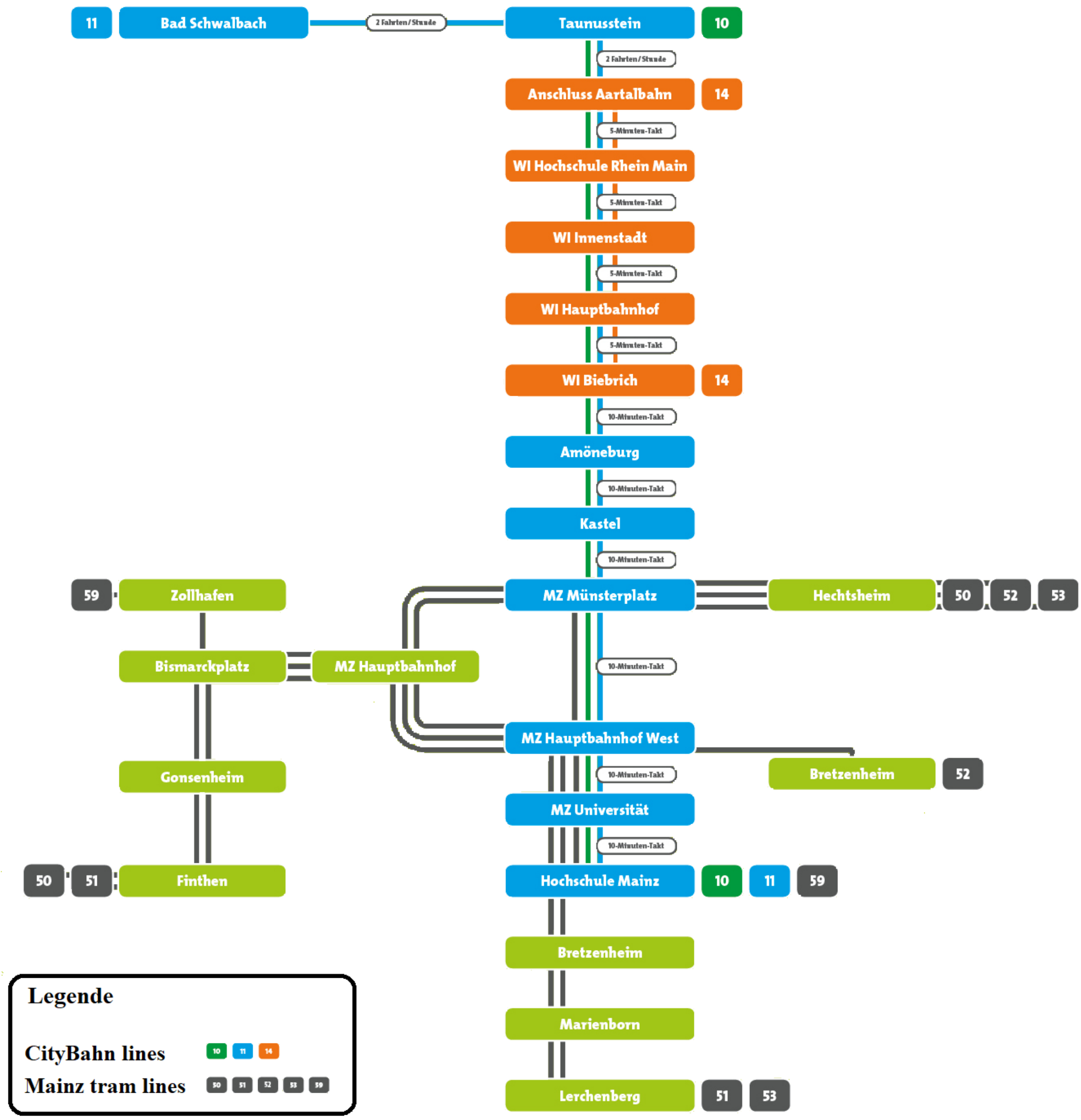

Figure 27 Planned tram stops and timetable for the CityBahn

Source: [37]

Figure 28 shows the line layout proposal of the CityBahn, route variants and alternative routes that will be precisely defined after the approval of the project plan. The entire line will be around 16 km long, while planning it is divided into 3 sections. The first section, running from Mainz Hbf to Kastel Brückenkopf will be 3 km long, the second section from Kastel Brückenkopf to Wiesbaden Hbf will be 10 km long and the third, from Wiesbaden Hbf to the Hochschule Wiesbaden 3 km long.

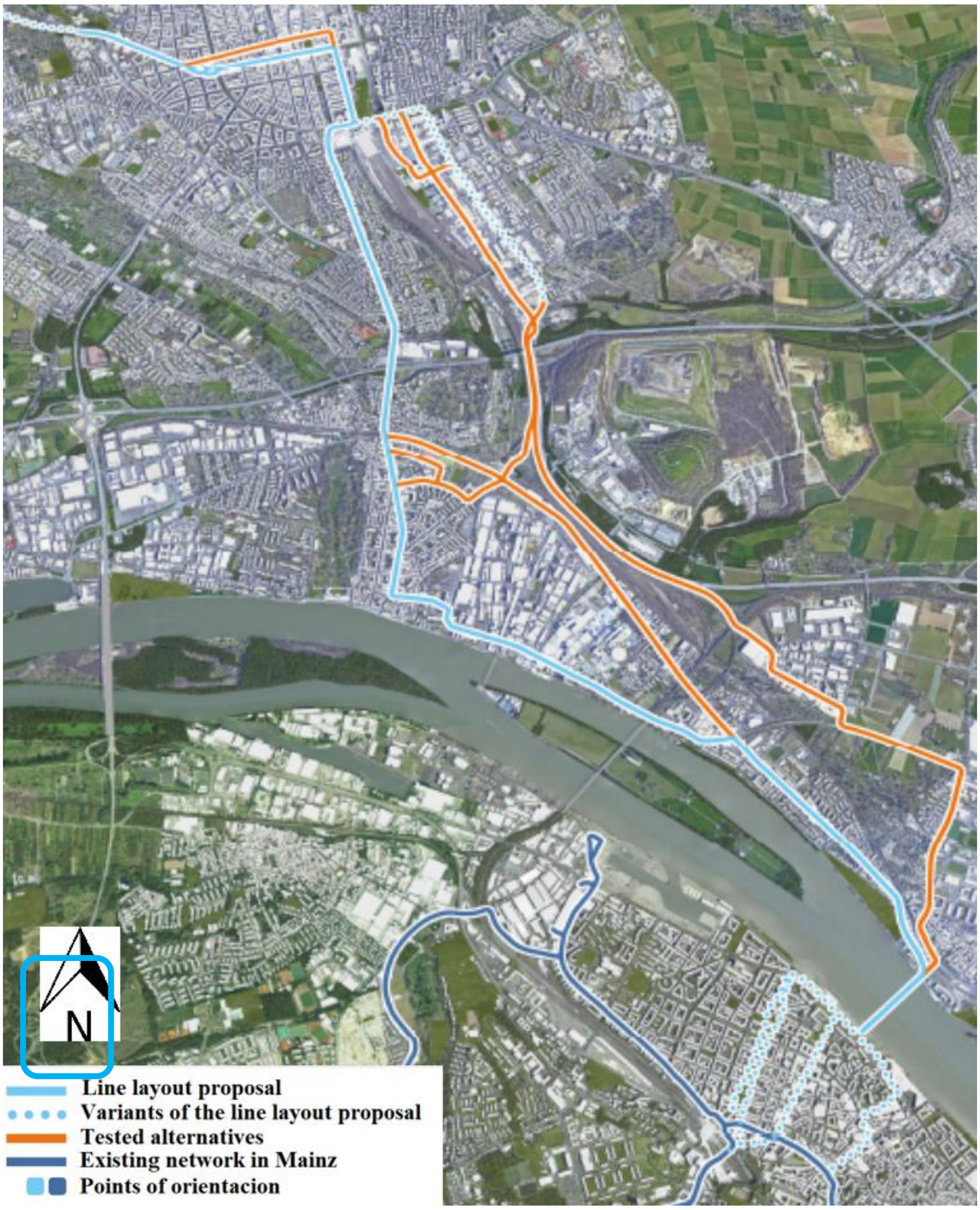

Figure 28 Wiesbaden tram route plan

Source: [37]

In addition to the growing Hochschule RheinMain, the stop of the CityBahn also links the densely populated Westend district to the rail network. At RheinMain University of Applied Sciences, an operational terminus for the CityBahn is planned for the first construction phase, at which the trams change direction. The trams of the CityBahn are designed for bidirectional operation, therefore turning loops are not needed. Sidings make it possible to take the trams flexibly into or out of service. [37]

Figure 29 Potential extension of the line

Source: [37]

The attractive labor market and the growing universities ensure ever-increasing commuter flows to Wiesbaden. Most commuters come from the Rheingau-Taunus district. Therefore, in a future project, the CityBahn line will be extended through the former Aartalbahn line to Taunusstein and Bad Schwalbach. The district council of the Rheingau-Taunus-Kreis has already declared that it wants to advance the project. [37]

4.3 ROLLING STOCK

Rolling stock for the first line has not yet been determined in detail. According to current calculations 38 vehicles are needed for the route Mainz - Wiesbaden - Bad Schwalbach, four of which are planned as reserve vehicles. The length of the vehicles should be approx. 35 m and run on a 1000 mm rail gauge in order to be able to operate on the existing tram network in Mainz as well. [40]

The greatest limitation in choosing the right vehicle type is that the line passes across the Theodor-Heuss-Brücke. The Theodor Heuss Bridge is an 475m long, arch bridge over the Rhine River connecting the Mainz-Kastel district of Wiesbaden and the Rhineland-Palatinate state capital Mainz. The main issue with the bridge is that both public transport vehicles and individual transport vehicles operate on it. When deducting the burden of traffic from personal cars, it was concluded that trams that would operating through this bridge could have a maximum axle load of 10 tons, preferably less. [39]

To avoid turning loops it is determined that the trams are designed for bidirectional operation and have a driver's cabin at both ends of the vehicle. [37]

4.4 ESTIMATED BUDGET OF THE PROJECT

The budget for the first stage of the project is estimated to be 420 to 480 million euros, which is intended to cover infrastructure costs and procurement of 38 tram vehicles. The budget allocation for infrastructure construction is shown in Table 13. The intended infrastructure budget amounts to 305 million euros, however, taking into account the possible overrun of the budget by 20%, that budget expands to 366 million euros. [39]

Table 13 Infracture costruction costs

	FROM	TO	BUDGET
SECTION 1	Hochschule Mainz	Theodor-Heuss-Brücke	34 million € (41 million €)
SECTION 2+3	Theodor-Heuss-Brücke	Hochschule Wiesbaden RheinMain	149 million € (179 million €)

Source: [39]

There are two main sections (second section is split in two), the first section joins the Hochschule Mainz and Theodor-Heuss-Brücke, which is a connection to the existing tram network in Mainz. While the second section from Theodor-Heuss-Brücke to the Hochschule Wiesbaden RheinMain relates to a new tram line that will be running in Wiesbaden. It is estimated that the length of the first section will be around 3 km, while the section two and three together will be around 13 kilometers long depending on which route will be finally chosen. From these data it can be calculated that the projected cost per kilometer route is approximately 11.5 to 13.5 million euros. [39]

A joint use of the Mainz tram infrastructure by the CityBahn is an integral part of the planning. Mainz mobility takes over the operation and maintenance of the CityBahn, thus the city of Wiesbaden does not have to build its own workshop facility's for the new trams. With this measure, the costs of the project can be significantly reduced. [37]

With regard to rolling stock procurement, the estimated budget amounts to 114 million euros for 38 trams, or 3 million euros per vehicle. The first plans estimate the need for 23 vehicles at any time on the tram line. The first plans estimate the need for 23 vehicles at any time on the tram line, 5 of which would operate on the first section of the tram line while the other 18 on the second and third. [39]

5 IMPLEMENTATION OF AN ALTERNATIVE SYSTEM ON THE FUTURE WIESBADEN TRAM NETWORK

When implementing an alternative system, it is necessary to determine the most important catenary-free locations of the future tram line and according to their requirements to choose an alternative system that will best meet the requirements with the most cost-effective investment. Furthermore, according to the needs of the network it is necessary to specify which vehicles meet the requirements. The greatest demand exists at the Theodor-Heuss-Brücke which has limited load, creating problems for the CityBahn planners.

5.1 POTENTIAL CATENARY-FREE NETWORK SECTIONS

During the planning of the first phase of the project, it was concluded that there are sites to be preserved, i.e. in the case of trams, to be constructed in catenary-free form. The most vulnerable are the three locations to which the tram network route passes, the locations are shown in Figure 30.

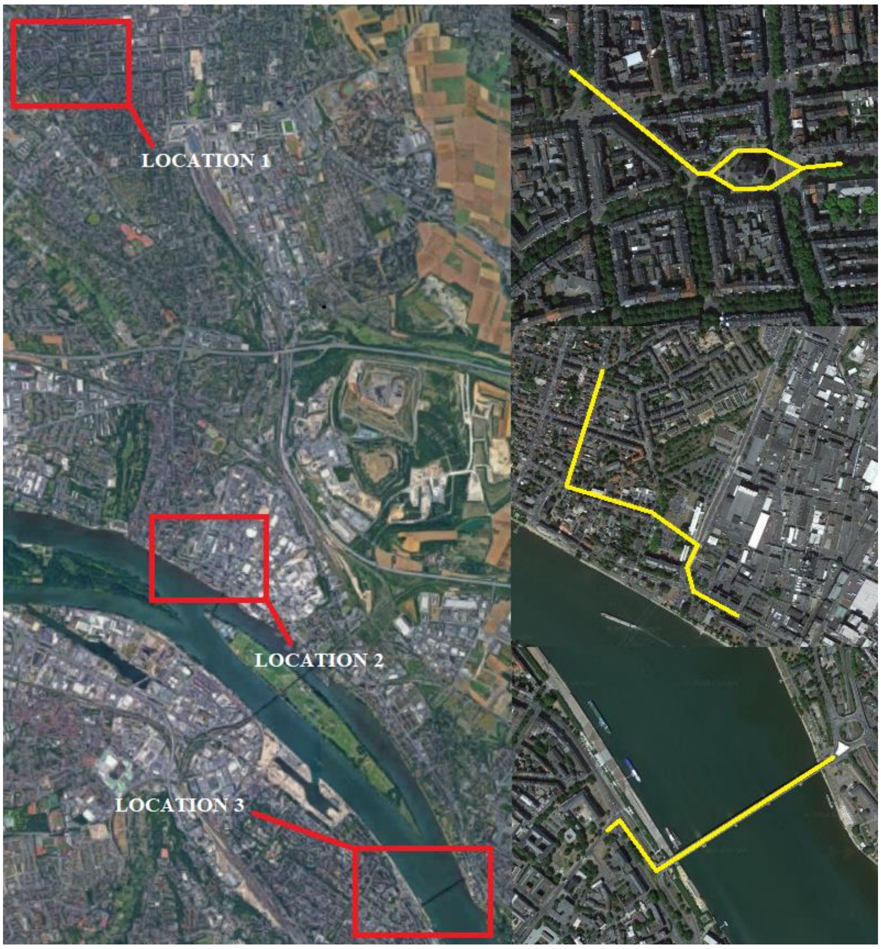

Figure 30 Potential locations for catenery-free application

Source: [39]

5.1.1 LOCATION 1

Location 1 is located in the center of Wiesbaden and goes through the Rheinstraße - An der Ringkirche - Klarenthaler Straße route. The location is delicate because it circulates around the Ringkirche church built between 1892 and 1894. The church is one of the symbols of the historic heritage of the city, and it is desirable to preserve its appearance.

In Figure 31 and Figure 32, an accurate route is shown for the part of the line passing through the first location and the planned start and end of the potential catenary-free zone is indicated, which would be between 800 m and 1km long depending on its beginning and end.

Figure 31 Location 1, Klarenthaler Straße - An der Ringkirche

Source: [37]

Figure 32 Location 1, An der Ringkirche – Rheinstraße

Source: [37]

In the case of a guided tour over the Rheinstraße, a long lasting problem would be solved by turning the zone around Ringkirche to a traffic-calmed zone without traffic that connects the Ringkirche with the surrounding areas. A stop would be located above the church ring. The residents of the Rheingauviertel, who do not yet enjoy optimal public transport, would then have direct access and benefit from the speed of the CityBahn. The location is only one stop away from the pedestrian zone and three from main station. [37]

5.1.2 **LOCATION 2**

Potential catenery-free section at the second location extends through the Rheingaustraße - Glausstraße - Adolf-Todt-Straße - Stettiner Straße route. In this section there are several cultural buildings and therefore there is a need for such infrastructure development. [37]

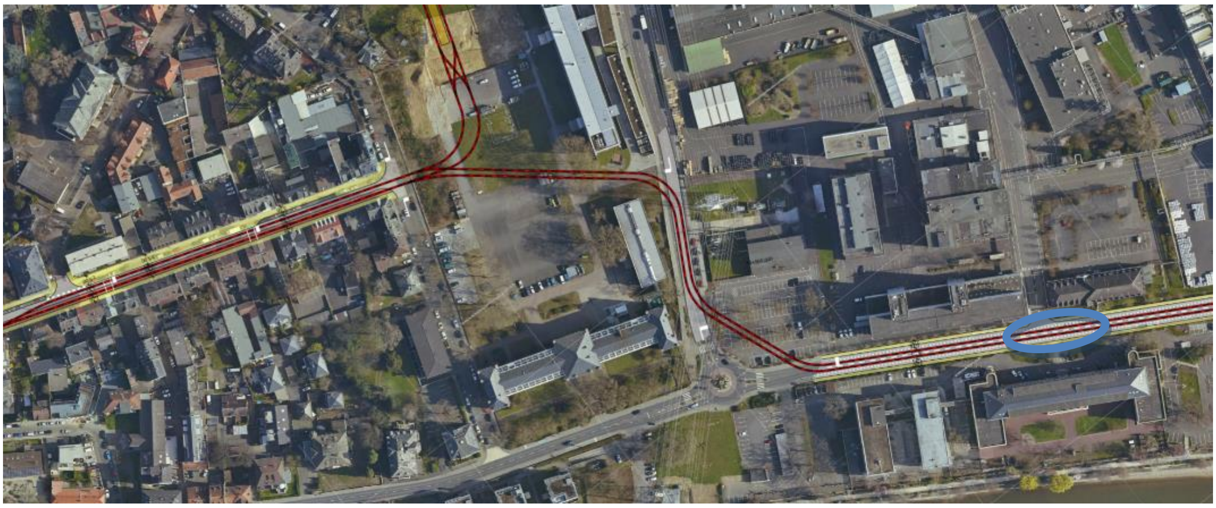

Figure 33 Location 2, Rheingaustraße - Glausstraße - Adolf-Todt-Straße

Source: [37]

Catenary-free stock would start roughly where it is shown in Figure 33 and extend to the location shown in Figure 34. The total length of the catenary-free stock would be about 1 km. [39]

Figure 34 Location 2, Adolf-Todt-Straße - Stettiner Straße

Source: [37]

The planners are currently setting the exact route through which the future tram line should pass, this route is currently under consideration. The occurring issue is the possibility of slightly lengthening the travel time of the total share from Mainz to Wiesbaden. [37]

5.1.3 **LOCATION 3**

The connection of the cities Mainz and Wiesbaden takes place in the first planning step over the Theodor Heuss bridge. The fastest way from the bridge with connection to the existing tram network of the Mainz transport company runs over the Große Bleiche street, where already the bus line 6 runs. In the course of the feasibility study in 2016, planners have already examined the route from the Theodor-Heuss-Brücke over the Große Bleiche and the Binger Straße to the main station West. The tested alignment continues into Mainz's existing network up to the University of Applied Sciences Mainz. [37]

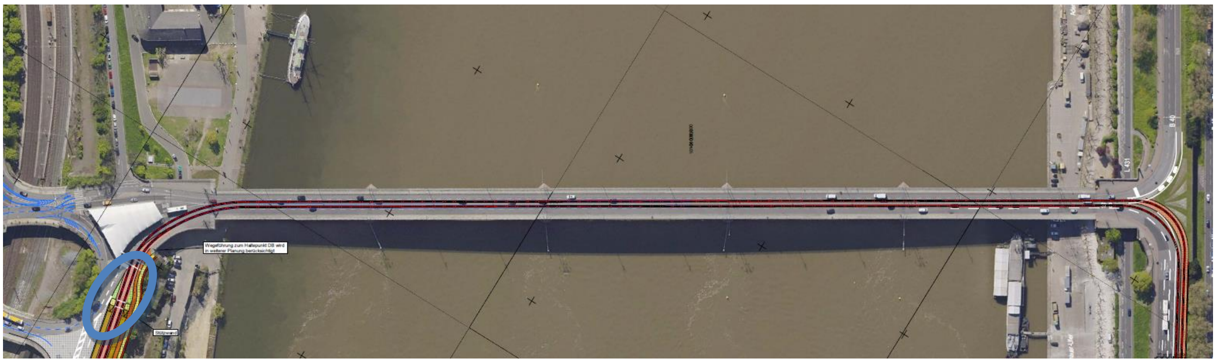

Figure 35 Location 3, Theodor-Heuss-Brücke

Source: [37]

The Theodor-Heuss-Brücke shown in Figure 35 was checked by the planners regarding their static requirements for a CityBahn traffic. The bridge meets the requirements, but at some points must be strengthened. These reinforcement measures take into account all listed building regulations and preserve the historical character of the bridge. [37] Static tests concluded that CityBahn could use axle load vehicles up to a maximum of 10 tons. [39]

In addition, a traffic simulation provided an outlook on the traffic flow on the bridge when used by the CityBahn. Accordingly, a new traffic light circuit will ensure that the realization of the CityBahn improves the access of cars to the bridge, also the traffic lights will give priority to public transport vehicles. On the Theodor-Heuss-Brücke it is planned that the traffic zone will be shared between the CityBahn and the rest of the individual traffic. [37]

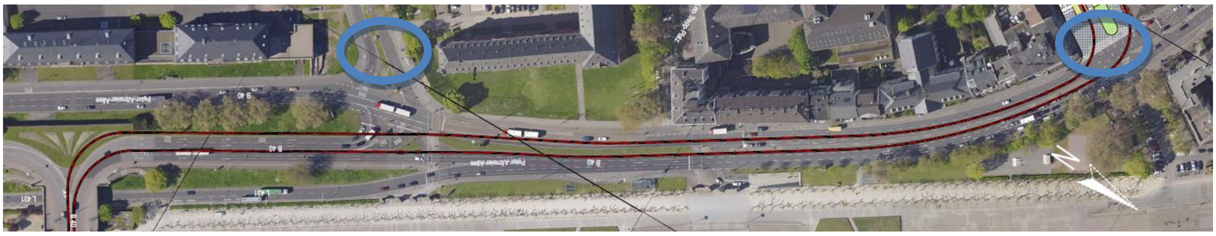

Figure 36 Location 3, Peter-Almeier-Alle - Große Bleiche – Rheinallee - Kaiserstraße

Source: [37]

There are currently two options to set up the route before continuing on the bridge from Mainz. The first and more probable option would be Große Bleiche - Peter-Almeier-Alle -

Theodor-Heuss-Brücke while the second and slightly longer option would be Kaiserstraße - Rheinallee - Peter-Almeier-Alle - Theodor-Heuss-Brücke. [37]

The Catenary-free zone would move from the beginning of Große Bleiche or Kaiserstraße depending on the route chosen, until the end of Theodor-Heuss-Brücke as shown in Figure 35 and Figure 36 and the length of the stock would be around 1 km. [39]

5.2 APLICATION AND SELECTION OF CATENERAY-FREE SYSTEMS

Designing a system for off-wire operation using periodic power transmission/energy storage devices is a complex task which must dynamically balance the energy stored on the vehicle against the energy requirements of the areas to be operated without an overhead distribution system. In order to optimize the type and size of the vehicle on-board energy storage devices used, a rigorous set of engineering calculations must be performed. The first step in this process is to accurately define the route and fully identify the areas where wireless operations are required and/or desired. The gathered information is used to perform standard propulsion system simulations that calculate energy consumption of both the propulsion performance and auxiliary power loads such as HVAC. Such simulations typically include:

1. speed limits and maximum operating speed
2. acceleration and braking performance
3. station dwell times
4. number and location of station stops
5. number and location of traffic lights
6. vertical grade details
7. any other alignment details and/or characteristics which may affect vehicle operations.

For the analysis of potential alternative system selection, a comparisons were made on catenary-free operations currently in revenue operations in other cities. Existing systems in revenue operations are classified into three categories, based on the maximum distance traveled off wire. The three categories are:

1. Distances greater than 1.6 km

2. Distances greater than 0.8 km
3. Distances shorter than 0.8 km. [41]

Table 14 summarizes some relevant technology applications around the world that could be used for comparisons for potential applications in Wiesbaden.

Table 14 Systems classified by catenary-free operation distance

System	**Catenary-free Distance > 1.6 km**	**Catenary-free Distance < 1.6 km**	**Catenary-free Distance < 0.8 km**	**Technology**
Boredeaux - Alstrom	🟦			APS - ground level
Augsburg - Bombardier			🟨	PRIMOVE
Nanjing - Bombardier	🟦			PRIMOVE
Nice - Alstrom		🟩		Battery
Almada - Siemens	🟦			Battery & Super-capacitors
Seville - CAF		🟩	🟨	Battery & Super-capacitors

Source: [41]

Blue and green colors have been labeled systems that can meet the needs of the city of Wiesbaden for the implementation of the catenary-free system, while the systems marked with yellow color are used in short distances and do not meet the needs of the city.

5.3 POTENTIAL SYSTEMS FOR IMPLEMENTATION IN WIESBADEN

Based on the data shown in Table 14, it can be concluded that most of technology's meet the conditions set by the distance that the vehicle should achieve catenary-free. To best exploit the potential of the tram network, it is necessary to choose the technology that will have the best ratio of the invested and obtained.

As can be seen in the first chapter of the paper, there are certain limitations, i.e. the positive and negative sides of certain technologies. When looking at technologies such as APS or PRIMOVE which use ground-level power supply, it is necessary to examine the quality of drainage systems on the routs where the trams would operate. When appropriate data is collected it is possible to determine the possible additional costs for implementing such a system. Such systems also multiply the initial investment in infrastructure construction and will therefore be eliminated or neglected in the next step of cost-benefit calculations.

For comparison of tram systems, three cases will be taken:

1. Standard or classic tram system
2. Battery tram system
3. Battery and super-capacitor tram system.

For all these cases, a cost-benefit analysis will be made according to the available data pertaining to each technology and the results will be presented as the economic benefit of the particular system.

5.4 COMPARISON OF VEHICLES

Due to the problem posed by Theodor-Heuss-Brücke and the limited axle load of a vehicle, it is necessary to choose the appropriate vehicle type that meets this requirement. Also with the limitation of the axle load of the vehicle to 10 t there is a demand for bi-directional vehicles to avoid the need for construction of roundabouts for trams at the end of the lines.

Three types of vehicles were selected that meet the requirements of planners, which are:

1. Škoda Forcity Smart
2. Bombardier Flexity Outlook
3. Siemens Avenio M.

Three different manufacturers were taken and compared to the features relevant to CityBahn. Of course, there are also other vehicle manufacturer’s that meet the requirements, but for those models, it is necessary to negotiate terms with the manufacturer in order to arrange the details of the vehicles.

Table 15 Comparison tramway vehicles

Type	Škoda Forcity Smart	Bombardier Flexity Outlook	Siemens Avenio M	
Model	bi-directional	bi-directional	bi-directional	
Length	27.6 m	27.6 m	27 m	36 m
Total height	3.83 m	3.5 m	3.5 m	
Maximum width	2.4 m	2.4 m	2.4 m	
Track gauge	1000 mm	1000 mm	1000 mm	
Number of seats	74+14	54	50	72
Number of standing spaces (4 persons / m2)	100	102	122	164
Car weight (empty)	43.4 t	37.9 t	unknown	
Car weight (loaded) (4 pass./m2)	54.6 t	49.8 t	unknown	
Engine power	8x64 kW	3x100 kW	unknown	
Maximum speed	80 km/h	70 km/h	70 km/h	
Minimum curve radius (horizontal)	15 m	17.5 m	unknown	
Minimum curve radius (vertical)	110 m	200 m	unknown	
Axle load	<8.5 t	9.1 t	10 t	

Source: [48] [49] [50]

According to the data it can be seen that there are three vehicles with different axle loads. All vehicles generally meet the requirements of the CityBahn and as such are applicable to the tram network, however, it should be taken into account that when vehicle upgrades are made by adding batteries or super-capacitors the weight of the vehicle changes and at the same time its axle load increases. Which can lead to the case that vehicles like Siemens Avenio M have to be eliminated because they exceed the maximum permissible load.

It is also necessary to negotiate with the manufacturers in order to maximize the tram vehicle's adjustment to the tram network and the requirements set. Through negotiations, it is possible to arrange for a vehicle price to be below 3 million euros, which is the current estimate by CityBahn planners of what the price of an individual vehicle would be. The price of vehicles will depend on the size of the fleet being purchased and it can be further lowered if the manufacturer can make upgrades to the vehicles as far as batteries and super-capacitors are concerned.

6 COST-BENEFIT ANALYSIS OF AN ALTERNATIVE TRAM SYSTEM IMPLEMENTED IN WIESBADEN

Benefits obtained through the implementation of the tram network in Wiesbaden can be shown in several forms. Generally, they are linked to the benefits of general traffic conditions and modal split, benefits for the users of transport services as well as the population which lives and works in that area and also benefits concerning the public transport carrier.

The usefulness factors of the CityBahn include, above all, travel time profits in public transport, the shift from private transport to public transport as well as the additional mobility options. Added to this are the car operating costs, the accident costs and the emissions costs.

At the same time, the CityBahn will bring a change in operating costs for the mobility provider, in this case ESWE Verkehr and Mainzer Mobilität. These include public transport operating costs with savings in comparison with the bus network, the maintenance costs for vehicles and routes, and personnel costs. When calculating the project's benefits also the maintenance costs for the rail infrastructure and the avoided investments are to be observed. These include the costs of measures that are omitted in the realization of the project, as well as depreciation and interest on the infrastructure.

The benefits of the CityBahn project are compared with the costs. These include the costs of the planned project for depreciation and interest on the infrastructure [40]

6.1 COST-BENEFIT FOR THE PLANNED TRAM LINE

The cost-benefit analysis is based on the data obtained by the PTV simulation of the impacts of the tramway implementation on the existing transport network. The demand data for the benefit-cost investigation are based on the demand model of the city of Wiesbaden. Traffic demand state of an average working day is simulated. The simulation is underpinned and calibrated using data from traffic counts and refers to the forecast of the period from 2016 to 2030. [40]

The population grows accordingly by about 0.3 percent per year. Growth for the city of Wiesbaden in the period of 2016 to 2035 is shown in Table 16.

Table 16 Wiesbaden population growth fot the period 2016 - 2035

	2016	**2020**	**2025**	**2030**	**2035**	**+% (for year 2016 - 2030)**
Wiesbaden	289,544	297,009	299,642	301,829	303,709	**0.30 %**

Source: [40]

In total, around five percent increase in population numbers is expected between 2016 and 2030. Expected growth in the number of jobs that will be roughly compatible with the growth of population. Similar growth rates are recorded in the cities of Mainz and Taunusstein. [40]

Summary of the most important structural data and traffic parameters for the period until 2030:

1. 20,000 more car journeys per day in Wiesbaden compared to the current state
2. Share of public transport in all motorized traffic in Wiesbaden will increse from todays 34% to 35% in 2030
3. 13% increase in traffic between Wiesbaden and Mainz (total traffic)
4. 10% increase in bus passengers until 2030. [40]

These data do not include the implementation of the tram network. Figure 37 shows the route used for the calculation, and shows very clearly that the CityBahn runs through areas with high population densities, in which further growth is expected in the future.

Figure 37 Tram route according to which PTV simulation was performed

Source: [40]

6.1.1 TRAVEL TIME

The travel time changes are determined for all passengers in the examination. Modifications that are less than five minutes per passenger are mitigated according to the Benefit Assessment Procedure Guide to allow for limited use of small individual travel time differences. Travel time savings of a passenger of only two to three minutes, for example, are only taken into account as a value of 50 percent. The assessment is made on the basis of procedural values. An hour of travel time saved is estimated to 7,10 Euro / hour. This value is independent of professional groups and income.

The average travel time over all passengers drops by about 36 seconds. The change in the travel time of all passengers affected is relatively small, since the number of passengers affected in total (basis of the evaluation) is very large, in total about 300,000 trips. Passengers affected include not only the journeys to and from the activities area, but all the rides that are affected by a change in the offer.

The travel time earnings calculated for a working day are multiplied by a factor of 300 days for one year, regarding adults. The extrapolation factor for school traffic is 250 days, each according to the requirements of the Standardized Assessment. [40]

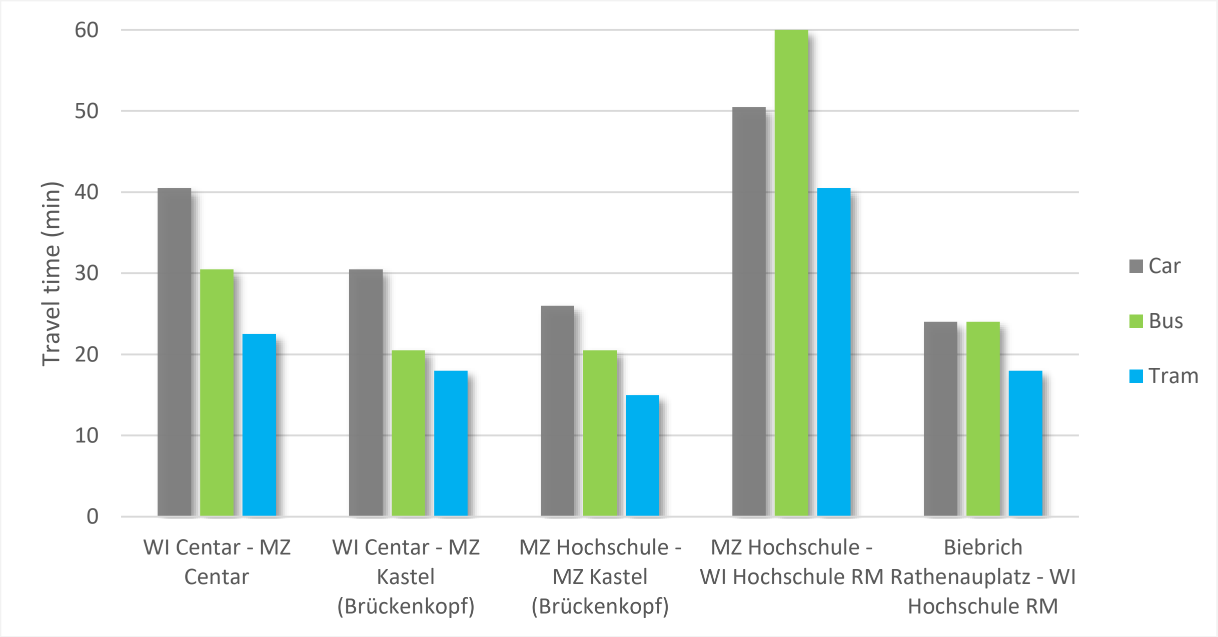

Diagram 2 Travel time comparison by modes of transport

Source: [40]

The travel time on the journeys affected when multiplied decreases by around 3,000 hours on a work day or by around 900,000 hours per year. This results in a benefit of 6.2 million euros per year. [40]

6.1.2 MODAL SPLIT

Also included in the Standardized Assessment procedure is a calculation formula for determining the modal split changes and thus a demand forecast, which provides the result of approx. 22,000 new passenger journeys in public transport. Approx. 17,000 of those journeys are avoided passenger journeys by car and approx. 5,000 new transports in public transport caused by induced traffic demand.

According to the standardized assessment, a car occupancy rate of 1.3 passengers per car is assumed. This value is uniform throughout Germany. This avoids around 13,000 car journeys on the weekday.

The apportionment of the public transport demand in the traffic model results in about 100,000 passengers for the CityBahn on the working day, i.e. in the forecast year 2030, around 100,000 passengers will use the CityBahn (between Bad Schwalbach, Taunusstein, Wiesbaden and Mainz) every workday. The strongest capacity utilization (around 40,000 passengers on the working day, i.e. approx. 20,000 passengers per direction) is to be expected for the section north of Wiesbaden main station.

The benefit from avoided car operating performance is closely related to the predicted passenger profits, as these are predominantly relocated away from passenger car traffic.

The avoided passenger car mileage results from the avoided car journeys (taking into account the car occupancy rate of 1.3 persons / car specified in the procedure and the extrapolation factor of 300 (workdays in one year)) and the travel distances, which were determined based on traffic models. The monetary valuation takes place via the valuation approaches given in the procedure. The cost rates of 0.22 Euro / passenger-km are specified in the procedure, as well as the distance and driving time from the traffic model determined.

As part of the demand forecast, transfers from the motorized vehicle to public transport were determined. This results in a car occupancy rate of 1.3 persons / vehicle are approx. 36.5 million avoided passenger car km / year. The economic benefit from avoided individual car operating costs thus amounts to around € 8.1 million per year. [40]

6.1.3 INDUCED TRAFFIC

Additional or improved mobility options create additional trips. This is called induced traffic (new traffic). The benefit component of the additional mobility options assesses the implicit benefits for public transport new traffic, i.e. for people who would not do the trips without the CityBahn and thus would be immobile.

The model-theoretical background of the calculation of this implicit benefit is that the overall benefit of the improved public transport offer from the point of view of these new customers is the same as the ticket price to be paid ahead added benefit of possible travel time improvements.

Specifically, this means that additional or improved mobility options will be used to make additional trips to the case of absence. For the additional benefit, the user is willing to pay the required ticket price.

As part of the demand forecast, the induced traffic was determined. According to the forecast formula of the Standardized Assessment, this amounts to around 5,000 passengers per day. The benefits of creating these additional mobility options amount to around € 2.2 million per year according to the Standardized Valuation Standard. [40]

6.1.4 **ACCIDENTS**

The accident cost rates of the vehicles (tram, bus and car) are specified in the procedure. The average amount of damage per year is determined by the changes in the public transport operating performance (light rail, bus) and the avoided car operating performance. [40]

Cost of road crashes is divided into two groups of costs:

1. Costs per casualty (medical costs, production loss, human costs, other costs)
2. Costs per crash (property damage, administrative costs, other cost) [42]

Due to the lower car mileage, the number of accidents in individual transport decreases. On balance, the benefit from avoided accident damage amounts to 1.5 million euros per year. [40]

6.1.5 **CO2 EMISSIONS AND OTHER POLLUTIONS**

The emission rates for CO2 as well as the valuation approaches of other pollutants are stipulated by the process. The trams also take into account emissions from electricity production. Changes in driving performance in public transport and motorized vehicles are used to determine the change in emissions. [40]

Table 17 The essential data for the calculation of the reduction of pollution

CO2 emission rates [g /car-km]:	127
CO2 emission rates electricity [g / kWh]:	414
CO2 emission rates for diesel (for diesel buses) [g / l]:	2774
Assessment of other pollutants [Euro / car-km]:	0.004
CO2 emissions [Euro / t]:	149

Source: [40]

Explanation of other pollutants: Emissions of pollutants such as sulfur dioxide (SO2), nitrogen oxides (NO), particulates, carbon monoxide (CO), volatile organic compounds (VOCs) that are generated during the generation or operation of vehicles.

Supplement to CO2: The emission rates and the assessment rates for pollutant emissions have been updated for the Version 2016 of the Standardized Assessment on behalf of the BMVI. An alignment with the approaches of the federal traffic route planning was made. While, according to version 2006, even average emission rates for passenger cars from 206 (out-of-town transports) to 261 (in-city traffic) per passenger-kilometer were used, this value has been reduced or updated to 127 g / passenger-kilometers in the 2016 version. This takes into account the developments in car vehicle technology and the changed fleet composition. The evaluation approach for each tone of CO2 avoided was reduced in the 2016 version from 231 euros (version 2006) to 149 euros. [40]

Calculation of emission reduction:

$$4{,}500\ t/CO2\, per\ year * 149\ € = 675{,}500\ \ €/year$$

$$36{,}500{,}000\ \text{passenger car km/year} * 0.004\ € = 146{,}000\ \ €/year$$

$$670{,}500\ \ €/year + 146{,}000\, €/year = 816{,}500\, €/year$$

The saved individual driving performance is followed by a reduction in CO2 emissions of approx. 4,500 t / CO2 per year. The value of the savings from other avoided emissions damages amounts to € 146,000 per year. [40]

Calculation of additional public transport pollution:

$$750\ t/CO2\,per\ year * 149\,€ = 111{,}750\ €/year$$

$$117{,}500\ €/year + 16{,}000\ €/year = 127{,}750\ €/year$$

Compared to this, the additional public transport damage resulting from the change in supply is significantly lower, the benefit loss amounts to approx. 130,000 euros per year (about 750 t / CO2 and additional other emissions worth 16,000 euros / year). [40]

Calculation of total change in pollution:

$$816{,}500\ €/year - 127{,}750\ €/year = 688{,}750\ €/year\ \approx 700{,}000\ €/year$$

On balance, the avoided emissions lead to an economic benefit of approx. 700,000 euros per year. [40]

6.1.6 PUBLIC TRANSPORT OPERATING COSTS

According to the calculation rule of the Standardized Assessment the public transport operating costs include:

1. the cost of capital for the procurement of trams and buses
2. the performance-related maintenance costs of the vehicles
3. the time-dependent maintenance costs of the vehicles
4. the energy costs of public transport
5. the personnel costs of public transport.

CityBahn GmbH calculated the cost of capital for the CityBahn based on a price of 3.0 million euros per vehicle. The approach is based on market prices for a conventional tram, which is 35 meters long and designed as a bidirectional vehicle. Detailed vehicle costs arise after the award of the tendered service.

Investments for vehicles are subject to the specified interest rate of 1.7 percent per annum. Depreciation of vehicle investments results from the prescribed depreciation periods of the standardized valuation. The cost-benefit analysis does not take into account possible vehicle support (for tram vehicles) but rather estimates the total procurement costs. All other cost rates that were used to assess the operating performance are specified by the standardized valuation in detail.

According to the procedure of the Standardized Assessment, a balance analysis is performed, which means that the operating costs with CityBahn are compared with the operating costs of his absence.

According to the current operational concept planning and the preliminary offer dimensioning, 38 vehicles (including reserve) are required on the Mainz - Wiesbaden- Bad Schwalbach route.

The CityBahn will provide operating services of 2.1 million kilometers per year. For the working day, the cost-benefit investigation is made for approximately 6,800 kilometers (all CityBahn lines together).

The vehicle and energy costs are higher in compensation, especially due to the higher procurement costs for tram vehicles than in the case of absence. In terms of personnel costs, however, savings are possible.

On balance, the public transport operating costs (excluding the debt service) increase by around 2.6 million euros / year after the implementation of the tram lines. [40]

6.1.7 MAINTENANCE COSTS

The planned infrastructure for the CityBahn, including all structures, railways, stops, power supply, control and safety technology, etc. is going to be maintained in the following years. This entails additional costs that go into the cost-benefit analysis. The standardized valuation provides for this so-called maintenance cost rates. These vary according to the respective maintenance costs of individual plant components.

The CityBahn project will rebuild the inner-city infrastructure consisting of road, media and canal. Even without the project CityBahn parts of the traffic areas, media and channel would be renewed. In accordance with the standardized valuation approach, these costs incurred are reduced for the amount of maintenance costs avoided by investments in the CityBahn project.

For the case of the implementation, the maintenance costs for the infrastructure were determined on the basis of the maintenance cost rates specified in the Standardized Assessment, subdivided according to plant components. After that, there will be additional maintenance costs of approx. 2.2 million euros per year.

This will be reduced by the annual costs of around 0.5 million euros, which will be avoided in the case of the tram infrastructure maintenance.

On balance, this results in additional annual expenses of around 1.7 million euros. [40]

6.1.8 INFRASTRUCTURE COST

The cost-benefit analysis is based on a cost estimate of the required infrastructure investment. This cost estimate corresponds to the planning status from December 2017 and therefore there might be some differences in view of the infrastructure costs regarding the last planed rout.

The investments in infrastructure include all costs for the planning and construction of the CityBahn. The most important cost factors are the construction of the route, the stops and the technical equipment.

Table 18 Infrastructure costs

Traffic routes public transport	Total cost
Track construction, substructure railways and roads, earthworks, supporting structures, bridges	€ 43 million
Track construction, superstructure roadway, roads and paths including bus lanes	€ 57 million
Stops, platforms and ramps, train control and signal systems, overhead lines, technical building equipment, noise control, landscaping, planting	€ 90 million
Total traffic routes public transport	€ 190 million
Relocation of third party equipment	
Roads and paths, including equipment	€ 30 million
Lines for electricity, telecommunications, gas, water, sewer, district heating	€ 38 million
Structures, vegetation and others	€ 12 million
Total relocation of third party equipment	€ 80 million
Planning	
Planning servicers	€ 27 million
Total	€ 297 million

Source: [40]

The infrastructure investments relevant in the economic evaluation amount to a total of approx. 270 million euros (2016 price level, excluding planning costs). In addition, according to the Standardized Assessment, a flat-rate of 10 percent planning costs must be applied.

The calculation of the capital service for the infrastructure costs of the mitigation is based on the preliminary cost estimate presented. The depreciation of infrastructure investments results from the depreciation periods, which are subdivided according to plant components and are specified in the standardized valuation. The investment for the track is paid at the specified interest rate of 1.7 percent per annum. This interest rate is adjusted for inflation and corresponds to the interest rate, which is also applied in the Federal Transport Infrastructure Planning for transport infrastructure.

The infrastructure investments relevant in the economic evaluation amount to a total of approx. 270 million euros (price level 2016) plus 10 percent planning costs. The resulting capital service for infrastructure investments is around 9.3 million euros per year. [40]

The latest version of the route is a fragment longer and its budget has increased to 305 million euros [39], which would mean that the annual cost would be 9.5 million euros, an increase of 200,000 euros per year. This evaluation may not be final given the possiblity of further alterations of the route during planning and thus the price of infrastructure may increase or decrease.

6.1.9 COST-BENEFIT RATIO

In determining the benefit-cost ratio, benefits and costs are compared. The benefits correspond to the balance of economic benefits, additional operating costs and additional infrastructure maintenance costs. The capital service of the infrastructure measure to be assessed is included as a cost in the valuation. [40]

Table 19 Sum of all financial benefits and costs on an annual basis for a standard tram system

Travel time	6,200,000 EUR
Modal split	8,100,000 EUR
Induced traffic	2,200,000 EUR
Accidents	1,500,000 EUR
CO2 emissions and other pollutions	700,000 EUR
Public transport operating costs	-2,600,000 EUR
Maintenance cost	-1,700,000 EUR
Sum of benefits	14,400,000 EUR
Infrastructure cost	-9,300,000 EUR
Annual profit	5,100,000 EUR

Source: [40]

Table 19 shows the sum of all benefits and costs in order to show how much the actual economic profit is on an annual basis after the construction of the tram network.

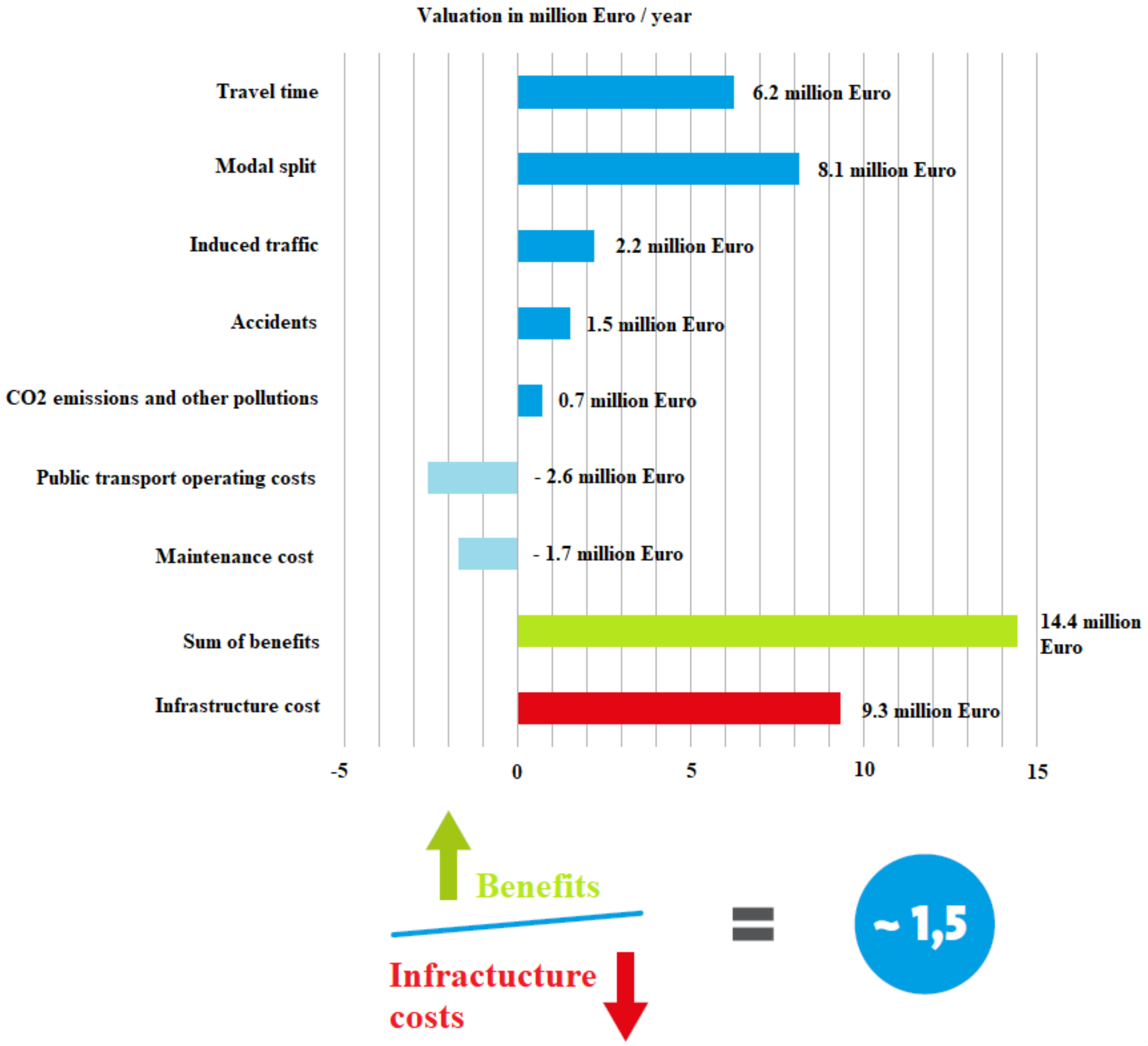

Diagram 3 Benefits and costs ratio in the case of a stardard tram system

Source: [40]

Overall, the current state of the cost-benefit analysis as shown in Diagram 3 for the entire CityBahn route from Bad Schwalbach to the University of Mainz provides a preliminary quotient of 1.5. Specifically, this means that every euro spent on the realization of the CityBahn brings an economic return of 50 percent. The value thus proves that with the CityBahn, the overall economic benefit clearly exceeds the anticipated costs of the project. Thus, the construction of the CityBahn is eligible.

The final cost-benefit ratio depends on a number of factors that may change as planning progresses. The current cost-benefit ratio of 1.5 is an intermediate state based on a number of other assumptions and forecasts made. The final cost-benefit quotient can only be determined shortly before the start of construction if the cost and benefit information is available in detail. [40]

6.2 COST-BENEFIT DIFERENCES AFTER IMPLEMENTING A BATTERY SYSTEM

Batteries are the most diverse type of on-board energy storage and include the traditional lead-acid, widelyused nickel cadmium types, as well as the newer nickel-iron, nickel-metal hydride, nickel-zinc, sodium-sulfur, lithium-iron disulfide, lithium-ion, lithium-polymer, lithium-thionyl chloride, lithium-sulfur dioxide, lithiummanganese dioxide, zinc-air, zinc-dibromide and numerous other types. Due to the wide variety, generalities concerning their performance characteristics, cost, weight, safety, maintenance and space requirements are difficult. Each battery type must be considered individually.

All types of batteries store energy chemically. The requirement of a chemical reaction results in a longer time to charge and discharge the battery with charging usually measured in hours, rather than seconds. The slow discharge rate usually results in a lower vehicle acceleration and overall performance. On the plus side, batteries can store more energy per unit weight than other on-board storage devices such as supercapacitors and flywheels. For long distances off-wire batteries are far superior to either supercapacitors or flywheels. [41]

All batteries also show a reduction in life based on the number of charge/discharge cycles and the depth of the discharge. Battery capacity is often oversized to minimize the depth of discharge in normal service. Typical expected lifetimes will be in the 5 to 10 year range while for the batteries that will be used in the cost-benefit analysis there is a guarantee for 15 years, while a longer life cycle is expected. [41] [44]

Improvements in battery performance are continuously emerging, driven mostly by developments for the automotive and cell phone industries. [41]

6.2.1 COST OF UPGRADING VEHICLES

Due to the very small number of available data on the costs of implementating batteries systems on trams, the data which is used to calculate the cost is based on vehicle expense data of the network in Midland, United Kingdom. The available costs information of the operator is recalculated from pounds to euros for a better comparison with the other options.

The cost can not be taken as definitive, but serves as an example for system comparison because it depends on multiple factors such as the dimensions of the vehicle and therefore the dimensions and capacity of the battery. Also, the cost varies depending on the number of vehicles involved in the implementation and the battery manufacturer.

Lithium ion cell batteries used for comparison are manufactured by companys CAF and SAFT. The cost of the battery system implementation on a fleet of 21 vehicles in Midland generates to 17.73 million euros in total. [44]

$$17{,}730{,}000\ €/21\ vehicle = 844{,}000\ €/vehicle$$

$$844{,}000\ €/vehicle * 38\ vehicles = 32{,}072{,}000\ € \approx 32\ million\ €$$

The cost of implementing a battery system on a single vehicle amounts to 844,000 euros based on the example taken. When this amount is multiplied by the number of vehicles intended for operation on the CityBahn, the cost of approximately 32 million euros is obtained.

$$32{,}072{,}000 * \frac{1.017^{30} * (1.017 - 1)}{1.017^{30} - 1} = 1{,}373{,}620\ €/year$$

If a vehicle repayment term of 30 years is taken with a specified interest rate of 1.7 percent per annum, battery implementation would generate an additional cost of approximately 1.35 million euros per year for the foreseeable period.

6.2.2 REDUCTION OF ENERGY CONSUMPTION

According to the first tests conducted by CAF in Spain, the battery system generates a 15% energy save on the comparative example. [47]

For the calculation, the data on the annual number of kilometers traveled and the average weight of trams were taken. In order to obtain the energy consumption expressed in kWh, it is necessary to multiply their multiplication with the average energy consumption of trams per tonne-kilometre.

$$2{,}100{,}100\ km * 50\ t = 105{,}000{,}000\ tkm$$

$$105{,}000{,}000\ tkm * \frac{91.4\ kWh}{1000\ tkm} = 9{,}597{,}000\ kWh$$

Once the annual consumption for the classic system is obtained, it is necessary to multiply it with a coefficient of 0.15 in order to obtain energy savings generated by the implementation of the battery system on trams. This consumption expressed in kWh is multiplied by the coefficient 0.12 representing the price of energy, ie the ratio € / kWh.

$$9{,}597{,}000\ kWh * 0.15 = 1{,}439{,}550\ kWh$$

$$1{,}439{,}550\ kWh * 0.12 = 172{,}746\ € \approx 175{,}000\ €$$

The savings of energy consumption compared to the classic tram system is around 175,000 € per year.

6.2.3 **REDUCTION OF POLUTION**

Based on the data of the battery tram system energy consumption reduction of 15% compared to a conventional tram system, pollution is also reduced by 15% compared to a conventional tram system. [47]

When calculating emission reductions, available data from the city of Wiesbaden was used and that part of the calculation remains unchanged compared to the convencional tramway system calculations because they are based on pollution reduction coused by the reduction in the number of vehicles and generally by the new modal split.

Calculation of emission reduction:

$$4{,}500\ \ t/CO2\ per\ year * 149\ € = 675{,}500\ \ €/year$$

$$36{,}500{,}000\ \text{ passenger car km/year} * 0.004\ € = 146{,}000\ \ €/year$$

$$670{,}500\ \ €/year + 146{,}000\ €/year = 816{,}500\ €/year$$

In order to obtain information on the new amount of CO2 and other gases, the data on the created pollution should be reduced by 15% and this amount multiplied by 149 € in order to gain the information of the economic burden of new pollution.

Calculation of additional public transport pollution:

$$750\, t/CO2\, per\ yrar * 0.15 = 112.5\, t/CO2\, per\ year$$

$$637{,}5\ \ t/CO2\, per\ year * 149\ € = 94{,}988\ \ €/year \approx 95{,}000\ \ €/year$$

$$16{,}000\, €/year - (16{,}000\, €/year * 0.15) = 13{,}600\, €/year$$

$$95{,}000\ \ €/year + 13{,}600\ \ €/year = 108{,}600\ \ €/year \approx 110{,}000\, €/year$$

To calculate the production of other new pollutants produced by tram vehicles, a coefficient of 0.15 was also taken, representing a reduction of 15%. So the new pollution costs around 110,000 euros a year.

Total reduction:

$$816{,}500\, €/year - 110{,}000\, €/year = \ 706{,}500\, €/year\ \ \approx 710{,}000\ \ €/year$$

So the total savings on pollution amounts to around 710,000 euros a year.

6.2.4 INFRASTRUCTURE SAVINGS

Data from the example of Midland, UK were used for calculating savings on infrastructure construction as well. The city claims it saves 10.6 million euros on a rout long 32 km by implementing a battery system on their trams, ie because it is not necessary to place overhead liners. [44] The information on the total length or percentage of the catenary-free route isn't available. In order to get roughly the assumption of the total length of these shares, the cost of placing overhead lines on the United Kingdom's track records was taken. According to their data for setting the overhead lane for two-way trams, it costs about 690,000 euros per kilometer of the route. [46]

$$\frac{10{,}600{,}000\ €}{690{,}000\ \ €/km} = 15.36\ km \approx 15.4\ km$$

$$\frac{15.4\ km}{32\ km} * 100 = 0{,}48 \approx 48\%$$

From these data it is possible to assume how many kilometers of the route are catenary free so that the total cost savings are divided by the cost per kilometer. After the calculation it turns out that about 15.4 km runs catenary-free, i.e. around 48% of the new network.

When calculating potential savings on infrastructure at the new network in Wiesbaden, it can be observed in two cases. The first case relates to the planned sections for which this technology is considered, these sections together accumulate to around 3 km in total length (three shares of 1 km), which is about 19% of the planned 16 km line. The other case involves calculating infrastructure savings on maximum potential utilization of technology, i.e. taking a percentage of lines as in Midland, which would be roughly 7.5 km of catenary free stock on the route.

Calculation of infrastructure savings based on first case data:

$$3km * 690{,}000\text{ €} = 2{,}070{,}000\text{ €} \approx 2{,}1\ million\text{ €}$$

If this amount of 2.1 million euros is allocated over a period of 30 years, it would be estimated that the annual savings would be around 70,000 euros for that period.

Calculation of infrastructure savings based on data from the second case:

$$7.5\ km * 690{,}000\text{ €} = 5{,}175{,}000\text{ €} \approx 5{,}2\ million\text{ €}$$

If the amount of 5.2 million euros is allocated over a period of 30 years, it would be estimated that the annual savings would be around 175,000 euros for that period.

Choosing the second option is more rational and the infrastructural savings could increase even more depending on the maximum potential for utilization of the technology on the tram network in Wiesbaden. However, to estimate the total distance that can be constructed, it is necessary to first decide on the vehicles and determine the type or model of the corresponding batteries according to available dimensions. Afterwards further tests are made on tracks with similar lengths and stop distances by the manufacturer to determine the maximum possible battery performance without loss of power and speed.

6.2.5 COST-BENEFIT RATIO

In order to obtain a benefit and cost ratio in the case of catenary-free infrastructure and vehicle upgrades, the data used to calculate them in the case of a conventional tram system are taken into account. Additional calculations are made only in categories where noticeable changes can occur.

Table 20 Sum of all financial benefits and costs on an annual basis for a battery tram system

Travel time	6,200,000 EUR
Modal split	8,100,000 EUR
Induced traffic	2,200,000 EUR
Accidents	1,500,000 EUR
CO2 emissions and other pollutions	710,000 EUR
Public transport operating costs	-2,600,000 EUR
Energy savings	175,000 EUR
Maintenance cost	-1,700,000 EUR
Battery implementation	-1,350,000 EUR
Sum of benefits	13,235,000 EUR
Infrastructure cost	-9,300,000 EUR
Infrastructure savings	175,000 EUR
Annual profit	4,110,000 EUR

Source: Author, according to the data from source [40]

Table 20 hows the sum of benefits and costs and how much profits are incurred on an annual basis when implementing such technology. It should be noted that the data used for the calculations is based on examples of other cities and may deviate from the calculations that would be made based on exact data directly related to the city of Wiesbaden.

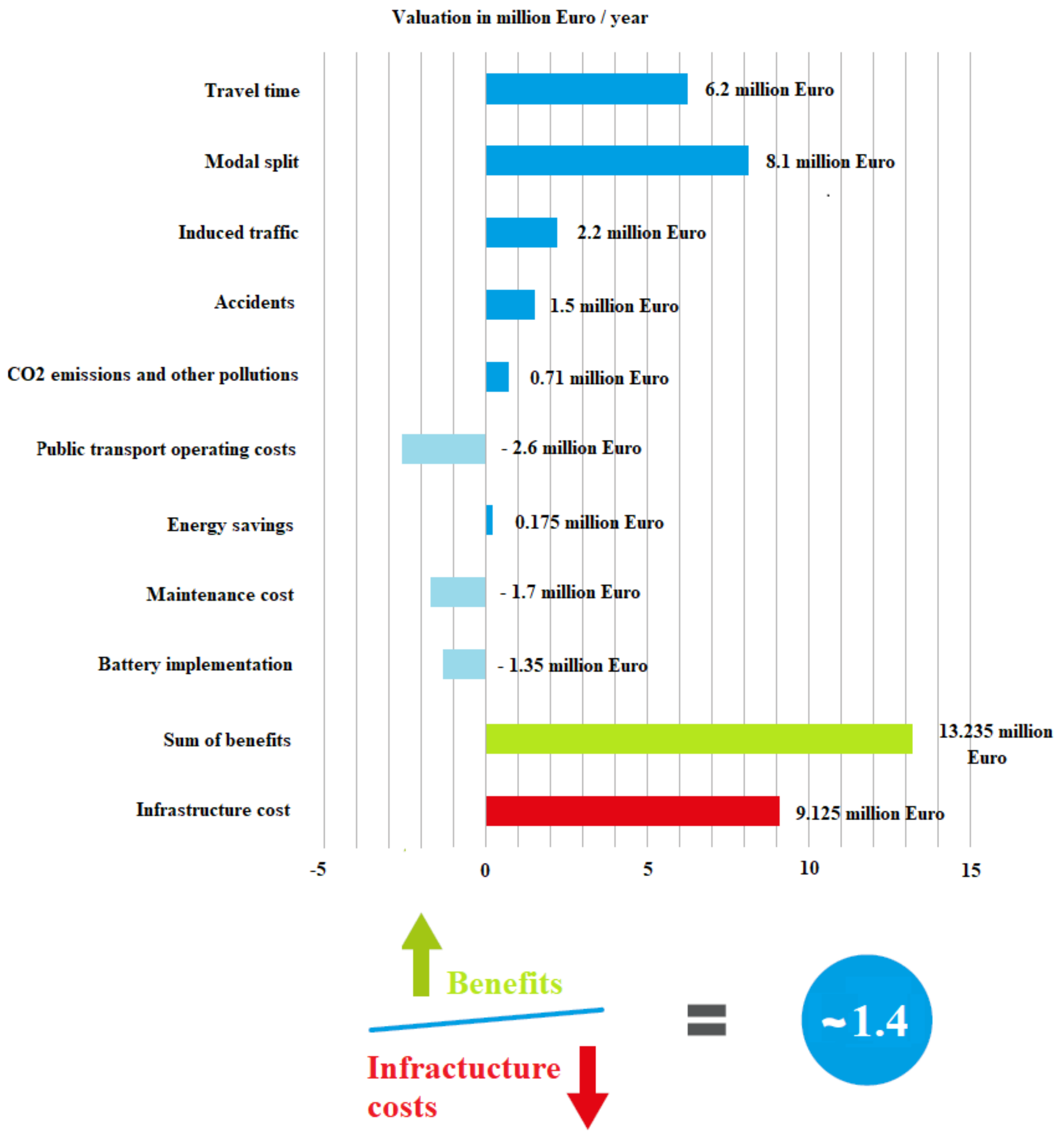

Diagram 4 Benefits and costs ratio in the case of an battery tram system

Source: Author, according to the data from source [40]

The coefficient of profitability falls from 1.5 to 1.4, but the value of preserving the historic core of the city and preserving the beauty of the rest of the city have not been added to the calculation. The value of this is difficult to show economically, there is a possibility of determining the coefficient due to a possible fall in tourism or general satisfaction of the population due to the installation of the catenary system in the city core and the distortion of the city's appearance.

6.3 COST-BENEFIT DIFERENCES AFTER IMPLEMENTING A BATTERY AND SUPER-CAPACITOR SYSTEM

Super-capacitors have much lower energy capacities compared to batteries but offer greater charge densities. Super-capacitors are able to capture power from braking sections of track through regenerative breaking, providing further charging and power generation capacities. The idea behind this hybrid system is the integration of both super-capacitors and batteries to obtain at the same time high power and energy densities.

The supercapacitor system charging/discharging rate is very fast, measured in seconds, and they can withstand repeated charge/discharge cycling without significant degradation over time. Design life does vary somewhat depending on the degree of cycling but has been claimed to be on the order of 23 to 30 years. [41]

6.3.1 COST OF UPGRADING VEHICLES

According to the current available data there are no examples of the cost of implementing a hybrid battery and super capacitors system. For the purposes of calculating the cost of implementation, the data on the implementation of the battery system in Midland, UK, and the data on the costs of implementing super-capacitors on the trams in Heidelberg, Germany, were used.

Public transport operators in Heidelberg equipped their trams with super-capacitors to preserve the arhitectural heritage of the city and operate without catenary overhead wires. The roof-mounted double-layer super-capacitor equipment costed 270,000 euros per vehicle. [45]

If the price of a super-capacitor of € 270,000 per vehicle adds a battery price of 844,000 euros per vehicle [44], the price of about 1.1 million euros is obtained. Since there is currently no better information, this amount will be used to calculate the implementation cost.

$$1{,}100{,}000\ €/vehicle * 38\ vehicles = 41{,}800{,}000\ €$$

When the implementation price is multiplied by the number of vehicles CityBahn plans to procure, the amount of 41.8 million euros is obtained.

$$41{,}800{,}000 * \frac{1.017^{30} * (1.017 - 1)}{1.017^{30} - 1} = 1{,}790{,}263\ €/year$$

Just as with calculating the cost of deploying the battery system alone, with a 30-year repayment plan and a specified interest rate of 1.7 percent per annum, the investment creates an additional cost of approximately 1.79 million euros a year.

This amount is not final and serves to approximate the difference in terms of the investment.

6.3.2 REDUCTION OF ENERGY CONSUMPTION

According to the data obtained on the example of the tram network in Almada, Portugal, up to 30% more energy is saved compared to the classic tram system. Consequently, the calculation of potential energy savings on the network in Wiesbaden was made. [17] [41]

For the calculation, the data on the annual number of kilometers traveled and the average weight of trams were taken. In order to obtain the energy consumption expressed in kWh, it is necessary to multiply their multiplication with the average energy consumption of trams per tonne kilometer.

$$2{,}100{,}100\ km * 50\ t = 105{,}000{,}000\ tkm$$

$$105{,}000{,}000\ tkm * \frac{91.4\ kWh}{1000\ tkm} = 9{,}597{,}000\ kWh$$

Once the annual consumption for the classic system is obtained, it is necessary to multiply it with a coefficient of 0.30 in order to obtain energy savings generated by the implementation of the battery system on trams. This consumption expressed in kWh is multiplied by the coefficient 0.12 representing the price of energy, ie the ratio € / kWh.

$$9{,}597{,}000\ kWh * 0.30 = 2{,}879{,}100\ kWh$$

$$2{,}897{,}100\ kWh * 0.12 = 345{,}492\ € \approx 345{,}000\ €$$

Energy savings compared to the classic tram system are around 345,000 € per year.

6.3.3 REDUCTION OF POLUTION

As with the reduction of energy consumption, the pollution production was reduced by 30% because they are directly connected to each other. [17] [41]

As with the first two cases, the reduction of pollution in the new modal split remains the same.

Calculation of emission reduction:

$$4{,}500\ \ t/CO2\,per\ year * 149\,€ = 675{,}500\ \ €/year$$

$$36{,}500{,}000\ \ \text{passenger car km/year} * 0.004\,€ = 146{,}000\ \ €/year$$

$$670{,}500\ \ €/year + 146{,}000\,€/year = 816{,}500\,€/year$$

New generated gases have been calculated in a way that data on new pollution of the classical tramway are taken and reduced by 30%.

Calculation of additional public transport pollution:

$$750\,t/CO2\,per\ yrar * 0.30 = 225\,t/CO2\,per\ year$$

$$525\ \ t/CO2\,per\ year * 149\,€ = 78{,}225\ \ €/year$$

$$16{,}000\,€/year - (16{,}000\,€/year * 0.30) = 11{,}200\,€/year$$

$$78{,}225\ \ €/year + 11{,}200\ \ €/year = 89{,}425\ \ €/year \approx 90{,}000\,€/year$$

To calculate the total reduction it is necessary to reduce the reduction of pollution generated by modal split by generated new pollution produced by the tram.

Total reduction:

$$816{,}500\,€/year - 90{,}000\,€/year = \ 726{,}500\,€/year$$

Total savings after taking into account new impacts on the implementation of batteries and supercapacitors on trams, amounts to around 725,000 euros a year.

6.3.4 INFRASTRUCTURE SAVINGS

By combining supercapacitors and batteries, up to 100% of the catenary-free infrastructure can be achieved, as in Dohe, Qatar. [41] It is mainly an area that is in the catenary-free use of about 80-90% of the total network and charging is carried out when the trams are held at stops. For the purposes of calculations, the lower limit of 80% is taken, as there is an additional cost of equipping the charging stations whose price is unknown and taking into account such a tram system it is necessary to get familiar with those costs directly by the manufacturer of those charging stations.

$$16\ km * 0.8 = 12.8\ km$$

The resulting length is then multiplied by the price of setting the catenary infrastructure, which is also taken in the example with the battery system only. [46]

$$12.8\ km * 690{,}000\ € = 8{,}832{,}000\ €$$

$$8{,}832{,}000\ € \ /\ 30\ years = 294{,}400\ \ €/year$$

Infrastructure savings could potentially amount to around 8.8 million euros, or around 295,000 euros a year over a period of 30 years.

6.3.5 COST-BENEFIT RATIO

Same as in the other case, the calculation is made of segments in which the changes occur. The calculation is based on a combination of data obtained from implementation examples in different cities and as such they may depart from a calculation that would have been made on the basis of data closely related to Wiesbaden.

Table 21 Sum of all financial benefits and costs on an annual basis for an battery and super-capacitor tram system

Travel time	6,200,000 EUR
Modal split	8,100,000 EUR
Induced traffic	2,200,000 EUR
Accidents	1,500,000 EUR
CO2 emissions and other pollutions	725,000 EUR
Public transport operating costs	-2,600,000 EUR
Energy savings	345,000 EUR
Maintenance cost	-1,700,000 EUR
Battery and Super-capacitors implementation	-1,790,000 EUR
Sum of benefits	12,980,000 EUR
Infrastructure cost	-9,300,000 EUR
Infrastructure savings	295,000 EUR
Annual profit	3,976,000 EUR

Source: Author, according to the data from source [40]

Data on economic benefits and costs are shown in Table 21 and also an approximate annual profit when implementing the battery and super-capacitor tram system in Wiesbaden.

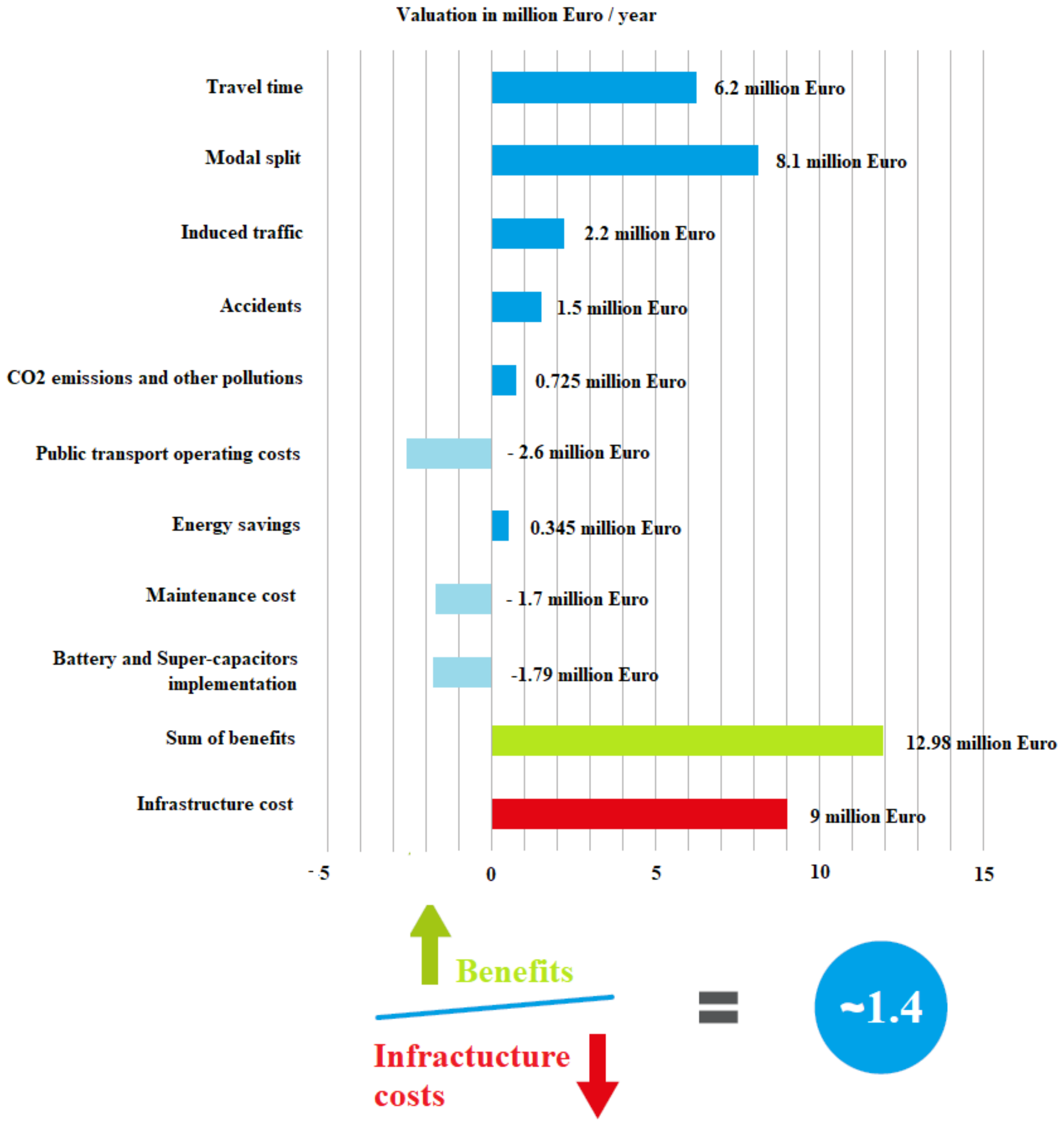

Diagram 5 Benefits and costs ratio in the case of an battery and super-capacitor tram system

Source: Author, according to the data from source [40]

6.4 COMPARISON OF COST-BENEFIT RESULTS

When comparing the costs and benefits and the profit made on an annual basis, it is clear that they do not stand out very much. Their comparison is shown in Diagram 6.

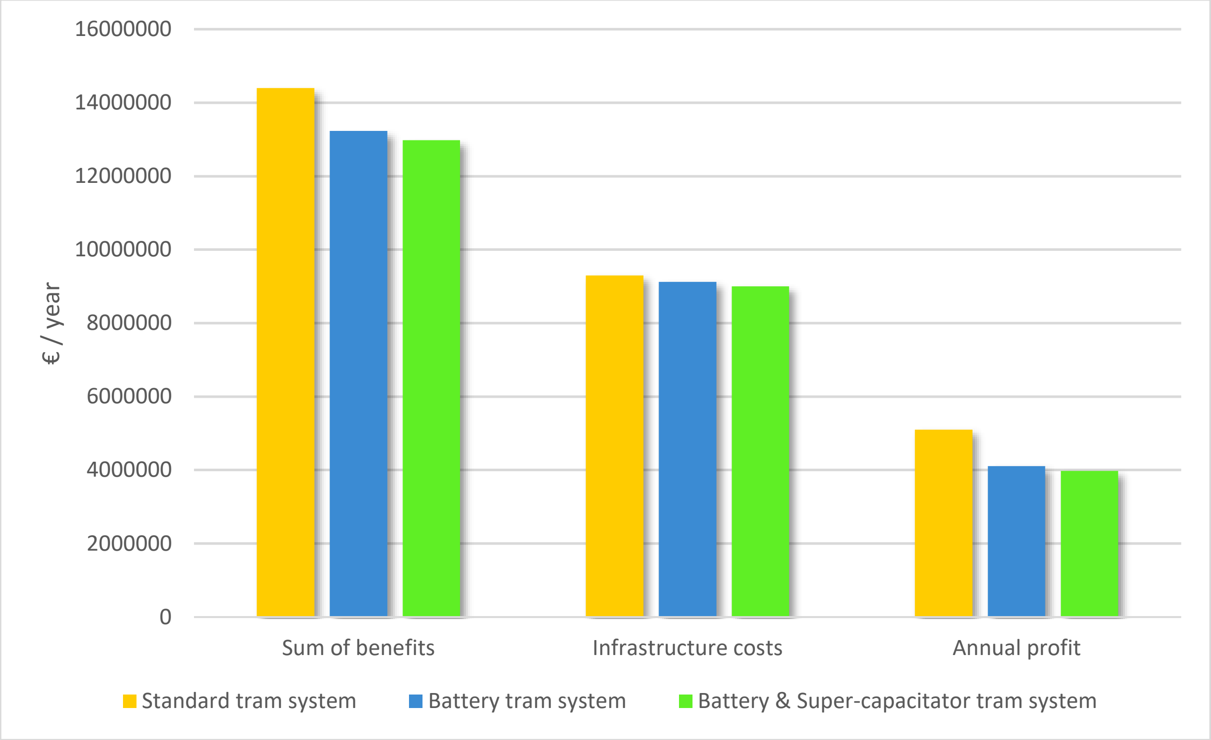

Diagram 6 Comparison of cost-benefit analysis results

Source: Author, according to the data from source [40]

The greatest difference is the cost that is needed to implement a new technology, and its benefits cannot be fully presented in an economic form. In order to show the true value of such systems, annual profit should be multiplied by a certain coefficient. This coefficient should be based on the data related to the acceptance and satisfaction of citizens by such tram system, the preservation of historical heritage, aesthetics of the city and other benefits that such a system brings and are not directly presented in an economical way.

The decision on the choice of the system to be implemented will need to be brought at the political level after a quality and fundamental analysis of all options has been carried out. The affordability and justification of the increased initial cost of infrastructure needs to be justified according to the needs of the city.

7 CONCLUSION

The implementation of tram networks in cities can bring many benefits to both public transport operators and customers. Tramway form of public transport contributes to the increase of income for the transport operator, by reducing the commuting and maintenance costs. Furthermore tram transportation brings environmental benefits by reducing the use of cars and buses and therefore reducing air polution . It also contributes to the mobility in cities by reducing traffic congestion, it generates urban development, better living conditions and therefore population growth on the areas of influence. And finally, it offers a better connection to the city centar.

In order to achieve the best transport service, it is necessary to meet the users preferences. Successful implementation of the tram system can be demonstrated through external factors such as network deployment, population growth and connectivity with different modes of transport.

For cities such as Wiesbaden the implementation of the catenary-free system is of great benefit in preserving the city's aesthetics and historical heritage. Catenary-free systems also contributs to the satisfaction of travelers, residents and citizens who gravitate to the area where the system is applied. The most sensitive locations in the city are listed in this paper, where the deployment of such technology is most needed but when using such technology it is necessary to take advantage of its full potential and maximum implementation, and this is achieved through detailed network tests.

There are many technologies that provide vehicle operation with catenary-free infrastructure, however the choice of technology needs to be made based on network requirements and limitations. Different technologies vary greatly with the cost of deployment, ground-level power supply technology requires the highest initial costs when building rail infrastructure and requires a high-quality drainage system. Technologies such as batteries and super-capacitors will achieve similar results with lower initial investments, and their implementation can be utilized in the event of an extension of the tram network that is planned in Wiesbaden after the construction of the first phase of the project.

Also when selecting the technology to implement it is necessary to take into account the potential further development of the used technology. Ground-level power supply technology is currently being developed by Bombardier and Alstrom, although it is the oldest of all catenary-free technologies it can be expected that its development will be slower than in the case of battery and super-capacitance systems developed by a large number of manufacturers, because a very similar technology is used on personal cars and buses. Because of an emerging market and demand for battery and super-capacitors developmant the conclusion can be draw that this technology will achieve the fastest progress and will result in a price drop of production and therefore cheaper procurement and maintenance.

Vehicle dimensions, the width and length of the vehicle are critical parts of the decision when selecting a catenary-free technology, given that the storage space, above or below the vehicle, would be limited when considering all other equipment needs. In Wiesbaden, there are two constraints to vehicle selection and thus the possible implementation of catenary-free technology. The first constraint represents a track width of 1000 mm, which is selected in order to merge the new Wiesbaden tram network with the existing tram network in Mainz and use their facilities for garaging and servicing vehicles. The other limitation is the Theodor-Heuss-Brücke, which allows a maximum axle load of 10 t for vehicles operating over it, which affects the implementation of technologies that use batteries and super capacitors, thus requiring an even lower vehicle axle load.

In the end, the decision on the implementation of the catenary-free system should be made after a accurate and detailed research has been carried out in order to see the actual utilization of such technologies in Wiesbaden with regard to the given constraints. Based on the results obtained, it is necessary to conclude how much the implementation of such technology is profitable and whether its benefits exceed the costs.

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LIST OF FIGURES

LIST OF TABLES

LIST OF DIAGRAMS

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U Zagrebu, 18.06.2018.

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