

Article

Tram System as a Challenge for Smart and Sustainable Urban Public Transport: Effects of Applying Bi-Directional Trams

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Abstract: Smart and sustainable urban public transport is a considerable challenge for contemporary cities. Society's ever-increasing transport needs require the search for solutions to increase the attractiveness of public transport. In view of the above, the main objective of this article was to determine what effects can ensue from applying bi-directional trams in the context of the smart and sustainable city concept. To attain the said objective, the research process involved desk research as well as primary research using the Delphi method, a case study, and the participant observation method. The research area covered by the study was the city of Szczecin, Poland. The completed research made it possible to identify the limitations of tram systems and the effects of applying bi-directional trams in cities, as well as to develop some practical applications for the city in question. The research study showed that application of bi-directional trams may contribute to improved functionality of a tram system, which is particularly important from the perspective of the smart and sustainable city concept. The results of this research study have both theoretical and practical implications.

Keywords: tram; bi-directional tram; public transport; sustainable transport; electromobility; electric vehicles; zero-emission vehicles; smart city; tram infrastructure



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1. Introduction

As a result of progressing urbanisation, most of the global population now live in cities, which entails specific effects. On the one hand, cities offer people better living conditions and better chances for personal development; e.g., as a result of access to the labour market, learning possibilities, culture, modern solutions, and innovations. On the other hand, cities have to cope with the negative effects of fast-paced urbanisation, such as excessive use of limited resources, waste overproduction, environmental pollution, traffic congestion, civilisation diseases, or irreversible functional changes of city space. In response to the indicated problems and challenges, a concept was devised to transform cities into smart and sustainable cities [1,2].

Among the numerous definitions of 'smart city' available in the literature, a very apt one from the perspective of this study came from Malasek [3], who said that in a long time horizon, a smart city should provide better and smarter public services that are more citizen-oriented, cost-efficient, and environmentally sustainable. In this approach, cities are faced by challenges in various areas of their functioning. In view of society's growing transport needs, a particularly important part of the smart and sustainable city concept is a smart, clean, and healthy transportation system [4]. Bamwesigye and Hlaváčková also indicated that attaining sustainable development in smart cities requires integration of reliable transport systems [5].

Implementation of the smart city concept in the area of urban transport may encompass various kinds of measures. These may include, e.g., application of new propulsion (e.g., electricity), new vehicle controls (e.g., intelligent transport systems), new business models (e.g., car sharing), and application of new regulatory measures and new transport planning

policies [4]. Moreover, in view of the current modal split in passenger traffic in Europe, which still shows a dominating share of passenger cars—73.4% compared to merely 1.4% for tram and metro combined [3]—the key element to meet the population's transport needs in smart cities should be, according to Bubelíny and Kubina [6], the possibility of making the public transport more attractive. Smart public transport is one of the key features of smart and sustainable cities [7], and its capability to effectively mobilise a large number of passengers is one of its key advantages over individual transport [8].

Public transport systems in cities comprise various components, which most frequently include buses, trams, metros, and urban rail systems (the latter are increasingly covering agglomerations and metropolitan areas). It should be noted that local authorities implementing the smart and sustainable city concept in the area of public transport should take into consideration each of the aforementioned components. Experiences of many European (including Polish) cities show that it is their bus systems that are subject to particularly intensive changes. However, in view of its properties, it is a both challenging and inspiring idea to include a tram system in the smart city concept implemented by cities. Trams are electric-powered and thus zero-emission vehicles. In addition to that, they feature a considerable passenger capacity and operate at a significant commercial speed, which enables them to effectively compete with individual transport. In this context, it seems reasonable to carry out research on possibilities and ways of using trams in the transport system of a smart and sustainable city.

Taking into account the various tram-system solutions found on the transport market, the main objective of this study was to determine what effects can ensue from applying bi-directional trams in the context of the smart and sustainable city concept. To attain the objective, it was necessary to carry out primary and secondary research and to find answers to the following research questions (RQs):

- **RQ1.** Does a tram system have features that curb its functionality?
- **RQ2.** What effects may be expected as a result of introducing bi-directional trams in cities?
- **RQ3.** Can bi-directional trams be an effective tool to improve the functionality of tram systems in cities?

The paper is divided into eight parts. The following part contains a literature review that presents the issues related to the impact of transport systems on the functioning of cities; the idea and assumptions of electromobility in transport, with a particular focus on public transport; as well as tram characteristics in the context of the smart and sustainable city concept. The third section of this paper presents the methodology and the study stages, along with a discussion of the research methods applied. The fourth section presents the results of the primary research carried out using the Delphi method in order to identify the limitations of a tram system functioning in a city. In view of the adopted main objective of the study, it was important to characterise the bi-directional tram and its operation principles, which is the content of the fifth section of this article. Moreover, a significant element of the fifth section was the identification of the effects of using bi-directional trams as a solution to improve a tram system functioning in a city. The sixth section presents a case study based on the example of the city of Szczecin, Poland. It evaluates the possibilities of implementing bi-directional trams in response to the challenges faced by the city in the context of smart and sustainable urban public transport. To sum up the research studies carried out for the purposes of this article, a discussion of the results is provided in the seventh section, while the eighth section contains a presentation of the conclusions and the theoretical and practical implications of the research conducted.

2. Literature Review

2.1. Issues Related to the Impact of Transport Systems on the Functioning of Cities

According to the forecasts available now, by 2050, city residents will account for as much as 68% of the global population (currently, this ratio amounts to ca. 55%) [9]. These estimates were confirmed by the research done by Tonne et al. [10], which showed that

urbanisation is the dominating trend in the demographical processes of the 21st century. The fast growth of cities to a large extent depends on the level of development of transport systems that are aimed at catering to the growing demand for passenger and freight transport. When analysing the importance of transport for the functioning of urban areas, it is also necessary to point out that, in addition to its obviously positive effects on society and the economy, transport is also a source of numerous hazards [11]. Its negative impacts are mainly due to the fact that most vehicles are powered by fossil fuels [12,13]. This leads to, e.g., air emissions of harmful substances such as: NO_x, CO, CO₂, PM₁₀, PM_{2.5}, and SO₂ [14–20], with global warming being the effect of increased levels of CO₂ in the atmosphere [21–23]. According to Aminzadegan et al. [24], within the European Union (EU) itself, transport is the second-largest source of greenhouse gas emissions. The literature provides numerous examples of studies demonstrating a strong correlation between traffic-related air pollution (TRAP) and human health [25–27]. There have been interesting studies regarding, e.g., cardiovascular diseases, conducted by Raaschou-Nielsen et al. [28]; asthma and COPD/chronic bronchitis, conducted by Jerrett et al. [29], Lindgren et al. [30], and Migliaretti et al. [31]; and acute changes in blood pressure, conducted by Weichenthal et al. [32]. One of the disturbing results of this research is that the high morbidity and mortality caused by traffic air pollution regards both the direct transport users (drivers and passengers) and other people using the urban space; e.g., residents living in houses located close to the roads or people involved in outdoor physical activities (e.g., joggers).

Other significant issues that were addressed in numerous studies that focused on the impacts of transport on the environment included traffic noise pollution [33–36], traffic accidents [37–40], and the related considerable social costs [41–44]. When analysing the negative impacts of transport, it is also worth mentioning the studies carried out by Caban et al. [45], Koźlak et al. [46], Bannani et al. [47], and Mir Shabbar Ali et al. [48] regarding congestion on the roads; and by McCahill et al. [49] and Wang et al. [50] concerning land consumption and land-use change. The presented research studies addressed transport congestion and its impact on the natural environment; moreover, they analysed the factors responsible for its formation. In addition, they indicated and discussed the tools that may be applied to curb congestion, such as improving the functioning of public transport or construction of Park & Ride car lots.

In the context of these studies, the following observation made by Yang et al. [51] seems very much to the point: city space is still subservient, mainly to the needs of the transport system and its effectiveness, whereas the inhabitants' needs are very often disregarded. Zacharias [52] underlined that urban motorisation contributes to construction of, e.g., signal-controlled intersections and fences, which constrain and control the pedestrian traffic to a significant extent. This issue was also addressed in a study done by Meethiyagod [53], who pointed out to the need to adopt 'new urbanism', the purpose of which will be mitigation of the conflict between the inhabitant (the pedestrian) and the transport system. As stated in the study by Angarita Lozano et al. [54], it is necessary to change the conventional urban planning models in order to create cities that are focused on the citizen.

To sum up, in accordance with the findings of Landersheim et al. [55], environmental pollution is one of the major current social problems of today, and taking measures aimed at mitigating such pollution will be one of the vital challenges of future mobility. In this aspect, sustainable transport development seems to be a key prerequisite necessary for improving the life quality of the ever-growing city population [56].

2.2. Electromobility in a City Transport System

As indicated by Deja et al. [57], one of the tangible aspects of measures aimed at mitigation of negative effects of transport activities is the EU transport policy. It promotes the forms of passenger and freight transport that contribute to a reduction in the environmental footprint of transport operations. A European Strategy for Low-Emission Mobility [58] pointed to three key areas in that regard: higher efficiency of the transport system, low-emission alternative energy for transport, and low- and zero-emission vehicles [33].

As stated by Mercik [59], electrification of the means of transport has a prominent place among EU measures. The aim of using electric-powered vehicles is to mitigate the harmful effects of transport operations on the environment [60]. When studying electromobility, defined by Macioszek [61] as the totality of issues connected with the use of electric vehicles, it must be noted that use of electric power to operate vehicles is not new. However, due to the technical constraints of electric power storage, for decades electromobility was reserved almost exclusively for the vehicles that could pull the power on a continuous basis from an external source during operation. As trains, trams and trolleybuses are equipped with pantographs; these vehicles have a possibility of taking power from an electric network, and for many years they have been able to meet the expectations connected with mitigating the adverse environmental impacts of transport. Guzik et al. [62] very aptly described this type of electromobility as first-generation electromobility; whereas the latter type of electromobility, in which vehicles are powered from an on-board source, is referred to as second-generation electromobility.

In terms of transporting the same number of passengers, public transport is considered to be more environmentally friendly than individual transport [63]. Therefore, it is not surprising that this form of transport is now undergoing significant transformations ensuing from electromobility goals. According to Kos et al. [64], electrified public transport may constitute the fundamental instrument to provide sustainable mobility in urban areas, even more so because for many decades, cities have been using electrified railway, tram, and underground systems. At this point it is also worth noting trolleybuses and the important role they play in meeting electromobility goals in cities, which was described extensively by, e.g., [65] Połom et al. [66], Wołek et al. [67], and Bartłomiejczuk et al. [68,69]. In these research studies, the authors pointed to a new possible path of development for this vehicle. Due to the development of alternative power sources (APS) and in-motion charging (IMC) technology, it also will be possible to further develop trolleybus networks in urban areas without overhead lines.

Unfortunately, the major problem of public transport is the adverse effect of urban buses on the natural environment. Hence, an important task is to successively replace fossil-fuel-powered buses with alternative-drive vehicles. In this aspect, there has been a sort of revolution—the bus market has undergone a significant change in that regard. At the first stage, a reduction in emissions of those vehicles was obtained via upgrading the EURO standard of the IC engine or switching to liquefied natural gas (LNG) and compressed natural gas (CNG). The effects of those changes were evaluated, e.g., by Morales Betancourt et al. [70], Jurkovič et al. [71], Krelling et al. [72], and Milojevic et al. [73]. The research results identified benefits such as reductions in noise, particulate matter, and greenhouse gas emissions. The subsequent stage was the use of hybrid vehicles; their effectiveness was examined, e.g., by Pawełczyk et al. [74] and Xu et al. [75]. They demonstrated that application of hybrid vehicles may bring substantial savings as a result of a decrease in fuel consumption, and in effect also a reduction in emissions, cutting down ca. 44% of NO_x emissions, 33% of total hydrocarbon emissions, and 51% of particle emissions. Moreover, they underlined the fact that hybrid buses do not require construction of any extra, costly infrastructures. Currently, most cities replace fossil-fuel-powered buses with fully electric vehicles. The practical benefits ensuing from operating this type of vehicle in selected cities were identified by, e.g., Konečný et al. [76] and Borén [77]. According to their findings, operation of electric vehicles may bring considerable benefits such as reduced emissions of harmful substances and noise, and consequently a reduction in social costs. Compared to fossil-fuel-powered buses, electric vehicles also feature a considerable reduction in energy consumption. However, in their research results, Pietrzak et al. [78] pointed out that attaining the full effects of electric-bus implementation depends on the country's energy mix. This conclusion was also confirmed by the research results obtained by Zimakowska-Laskowska et al. [79].

As demonstrated by Perumal et al. [80], Jiang et al. [81], Pamuła et al. [82], and Javanowicz et al. [83], in addition to the evident advantages of electric buses, the process of

their implementation can encounter numerous problems. Electric buses are much more expensive to purchase, and in addition to that, they require a special infrastructure to enable battery charging (also outside bus depots). Vehicles powered by on-board batteries have considerably limited travel ranges, and they need time to recharge the batteries, which requires changes in transport organisation. This results in a need to introduce technical breaks, and consequently, it is necessary to adjust the entire timetable. As a result, electric buses are currently less flexible than conventional diesel-powered buses. According to Astaneh et al. [84], marketing of second-generation electromobility vehicles poses specific requirements; i.e., extending battery lifespan and vehicle travel range. Janota et al. [85] also pointed to the problem of battery disposal when batteries lose the capacity necessary to ensure effective operation of the vehicle. They also noted that losing as little as 20% of the battery's initial capacity makes it necessary to discard it.

2.3. Tram in the Smart and Sustainable City Concept

The research conducted by Żochowska et al. [86] demonstrated that, in terms of sustainable mobility, a tram system is the most promising subsystem of public transport. This may be due to, among other things, a considerable capacity of this means of transport (which was also underlined by Khelil et al. [87], Fang et al. [88], and Damayanti et al. [89]), enabling fast and efficient handling of large traffic flows. As shown by Guerrieri [90], a tram's commercial speed may be up to 30 km/h, whereas a tram line's efficiency in one direction may be up to 6000 passengers per hour. With reference to the features indicated above, Alpkokin et al. [91] stressed the significant potential of trams in terms of the possibility of reducing traffic congestion. However, when considering the role of trams from the perspective of sustainable development, it seemed that the most important feature is that they are zero-emission vehicles. According to Moreno et al. [92] and Savchuk et al. [93], trams may be considered the most environmentally friendly form of public transport.

In addition to the above-mentioned features, an important aspect of applying a tram system to implement the smart and sustainable city concept is the potential for making densely built areas greener. Green tram tracks (GTTs) are a concept that assumes the utilisation of tram infrastructures to develop vegetated areas that may contribute to improvement of air quality in cities [94] or to a reduction in noise and vibrations generated by trams [95,96]. In this respect, an interesting research study on tram system development in Warsaw (Poland) was carried out by Łukaszewicz et al. [97,98]. According to their findings, GTT development or skilful integration of a tram track with the surroundings may contribute to creation of 'friendly tram routes'. In their research, the authors also indicated a possibility of adapting the already-operated tram routes and designing new ones in accordance with the 'green point of view'. Thus, a tram system may become a backbone of green corridors across the city.

According to Solecka et al. [99], one of the conditions for obtaining efficient public transport is reduction in its energy consumption. Therefore, it is not surprising that many researchers focus on evaluating the possibility of using energy recovered from tram braking for tram propulsion [100,101]. The solution may contribute to a significant reduction in tram system operation costs in cities, and ultimately to a reduction in emissions of adverse substances generated in the course of electric power production. Other studies focused on the potential possibility of reducing the power consumption via utilisation of telematics tools to control the tram traffic and give it priority in the form of a 'green wave' [102]. The idea of public transport prioritisation was also highlighted by Rabay et al. [103], who also pointed out that such investments make it possible to increase the number of passengers. Promising findings in that regard were obtained by Czerepicki et al. [104], who stated that giving priority to tram traffic in a city may lead to a reduction in energy consumption exceeding 20%. Failing to take measures aimed at tram prioritisation in urban traffic may limit the possibilities of smart transport development, which was proved by Courtois et al. based on the example of Brussels [105].

As indicated by Postatskyi et al. [106], due to the fact that tram features align with the idea of a smart and sustainable city, there has been a sort of revival of tram transport over the recent years. New tram systems are being developed, even in the cities that many years ago totally abandoned this form of transport and eliminated the entire infrastructure. A vital role of a tram system was also identified by Bouquet [107], who observed that currently, trams are becoming a symbol of a cultural mutation in urban development planning. The research conducted by An et al. in China [108] showed that appropriate development of tram systems may be treated as one of the major indicators of a city's development level. Moreover, a tram system may also be a kind of showpiece of a city, which was confirmed by the findings of extensive studies in this respect conducted by Richer [109]. Thus, a tram system changes the perception of a city, and a city with a tram system may be perceived as modern and attractive by residents, tourists, or businesses.

Summing up, trams are zero-emission vehicles characterised by a considerable passenger capacity and a significant commercial speed. As long as appropriate conditions and traffic priorities are ensured, trams may almost totally avoid traffic congestion. Due to their features, trams may also efficiently handle large passenger flows, including in crowded city centres. The permanent power supply from the external network enables trams to avoid problems still faced by electric buses. Thus, a tram's daily quantity of passenger-kilometres is not limited by battery capacity; moreover, it is not necessary for them take technical breaks for battery recharging.

The current literature addresses a wide range of issues connected with public transport functioning and its role in the implementation of the smart and sustainable city concept. Unfortunately, only few of those studies directly or indirectly pertained to tram systems. This may be due to the fact that a considerable number of the studies involved searching for alternative solutions to replace internal combustion engines, which could mitigate the negative environmental impacts of transport. Thus, the studies mainly focused on developing subsequent generations of buses, while tram systems, being first-generation electromobility zero-emission systems, were outside their areas of interest. However, measures aimed at replacing fossil-fuel-powered buses with electrically driven vehicles will not solve all urban transport problems—application of EVs does not bring tangible effects of reductions in traffic congestion or the number of accidents [110]. Hence, it seems reasonable to engage in research on other means of public transport, such as trams.

The existing papers on tram systems focused mainly on evaluating the impacts of constructing new routes on city development, as well as on analysing the solutions aimed at reducing the demand for electric power used by trams or reducing noise made by trams. We found no publications regarding tram system limitations or the possibilities and potential effects of applying bi-directional trams.

This article is therefore a response to the existing literature gap in the area of tram system limitations and the possibilities of improving tram system functionality. Moreover, based on a case study carried out for the city of Szczecin (Poland), the article also presents practical aspects of applying bi-directional trams in the city.

3. Methodology

This article describes research on the effects of applying bi-directional trams in urban public transport in the context of smart and sustainable cities. The research was conducted based on a case study using the example of the city of Szczecin. The research process was divided into 7 stages:

- Stage 1: literature review conducted in the following areas: impacts of transport systems on cities functioning, electromobility in urban transport systems, and the role of trams in the smart and sustainable city concept. As a result of the literature review, the literature gap, research objective, and research questions were formulated;
- Stage 2: identification and description of tram system limitations that may have an impact on functionality in a city (the Delphi method);

- Stage 3: providing the characteristics of the bi-directional tram as a means of transport, along with the principles of its operation;
- Stage 4: effects of applying bi-directional trams in a smart and sustainable city;
- Stage 5: description of the research area; i.e., the city of Szczecin, along with an analysis of its public transport system;
- Stage 6: development of practical aspects of using bi-directional trams in the public transport system in Szczecin, Poland;
- Stage 7: discussion of the results and formulation of conclusions ensuing from the completed research study.

The following research methods were used for the purposes of this research study:

- Literature review—the research method that made it possible to collect and synthesise previous research results [111] regarding the issues addressed;
- The Delphi method (also referred to as the Delphi expert consensus method [112])—tram system limitations were identified via obtaining the convergence of opinions expressed by the expert panel [113] ($n = 26$) in an iterative research process;
- Case study—method consisting of an intensive study of a specific entity, making it possible to generalise the conclusions and extend them to several entities [114], which enabled a detailed examination of the tram system in the city of Szczecin in the context of applying bi-directional trams;
- Participant observation method—this method engages the researcher directly in the studied situation, phenomenon, entity or community, making it possible to record what is being observed [115];
- Analysis and synthesis methods—general methods that are characterised by a considerable level of universality.

The research process followed in the course of the study described in this paper is presented graphically in Figure 1.

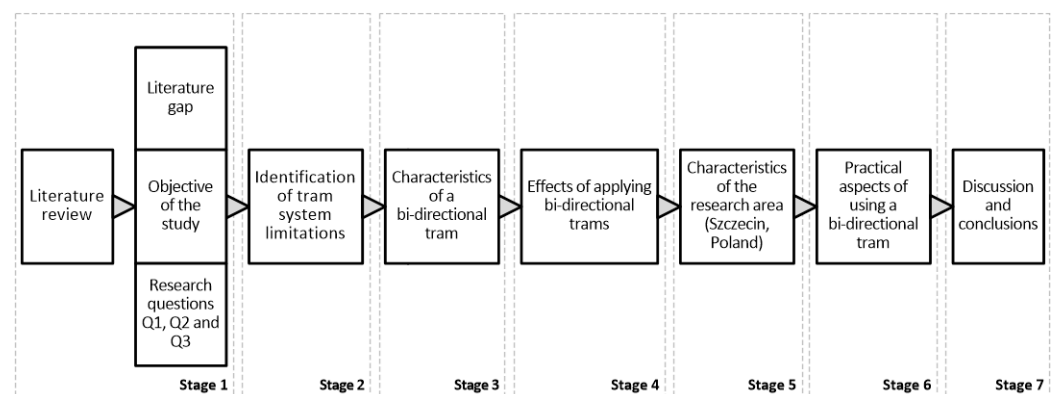


Figure 1. The research process flow diagram.

A significant issue found in the area of the object of the research conducted by the authors of this paper was the diverse nomenclature of some elements of a tram system. In order to ensure appropriate understanding of the issues discussed here, the following concepts should be construed as follows:

- Tram line—a tram connection specified in the timetable, identifiable by a number and the names of the termini;
- Tram route—an element of a tram infrastructure; a section of a tram track from one terminus to the other;
- Tram loop—an element of a tram infrastructure; usually located at the beginning/end of a tram route, it makes it possible for a tram to change the travel direction by turning around along the specially curved track;

- Switch-back terminal—an element of a tram infrastructure; usually located at the beginning/end of a tram route, it makes it possible for a bi-directional tram to change the travel direction without the need to turn around at a tram loop;
- Temporary switch-back terminal—an element of a tram infrastructure that may be temporarily installed on top of the existing tracks to maintain the tram traffic during maintenance work.

4. Identifying the Limitations in the Functionality of Uni-Directional Tram Systems

In order to identify the limitations of tram systems that impact their functionality in city public transport systems, an iterative research process was carried out using the Delphi method. This method makes it possible to examine a concrete issue via obtaining, analysing, and synthesising anonymous opinions of a group of experts during a series of subsequent rounds. The number of rounds depends on obtaining a consensus for a given issue; usually this takes from two to five rounds. The questions in the next round are based on the findings ensuing from the previous round, and experts are informed about the views of the other, anonymous experts; in subsequent rounds, they may also change or correct their earlier opinions [116]. This approach enables the study to evolve over time.

Due to the fact that there are no generally agreed criteria for selecting experts and there are no guidelines on the minimum or maximum number of experts in a group [117], the expert panel should be composed in such a way so as to possibly obtain the best and the most comprehensive opinions on the examined issue [118]. In view of the above, the expert panel defined by the authors of this paper comprised 26 persons representing various environments; i.e., those of science, business, and public administration. Due to the fact that the study regarded identification of tram system limitations in the conditions prevailing in Poland, it was assumed that the experts should have expertise and/or professional experience in public transport functioning in Poland. Finally, the structure of the expert panel engaged in the study was as follows:

- 6 persons represented research centres (universities conducting studies on public transport systems);
- 5 persons represented public transport authorities (local administration units);
- 5 persons represented tram operators;
- 2 persons represented tram manufacturers;
- 5 persons represented consulting associations and organisations operating in the area of public transport;
- 3 persons represented the business environment connected with urban transport.

The Delphi method study took three rounds. In the first round, the experts were asked to express their opinions on limitations of tram systems that they identified. Opinions obtained from the individual experts were diverse; in addition, the views were formulated differently, taking the form of a list or a verbal description. In the next stage, the authors of this paper analysed the collected opinions. The analysis showed that the limitations indicated by the experts pertained to three different levels of the tram system functioning in a city:

1. Design and construction of a new tram system in a city (L1);
2. Operation of an existing tram system in a city (L2);
3. Extension of an existing tram system in a city (L3);

As a result of the completed analysis, the listed limitations indicated by the expert panel were systematised by assigning them to one or more of the levels and then standardised in formal and linguistic terms. A diagram was prepared and handed over to the experts in Round 2 for verification. In that phase, some experts made corrections and additions to their responses. The analysed (for the second time) list of limitations was re-systematised and categorised by the authors of this paper, and the results were presented to the experts in Round 3. Round 3 resulted in the desired consensus among the experts and made it possible to develop a systematised and cohesive list of tram system limitations.

The diagram showing the prepared list of limitations broken down according to the defined levels of tram system development is presented in Figure 2.

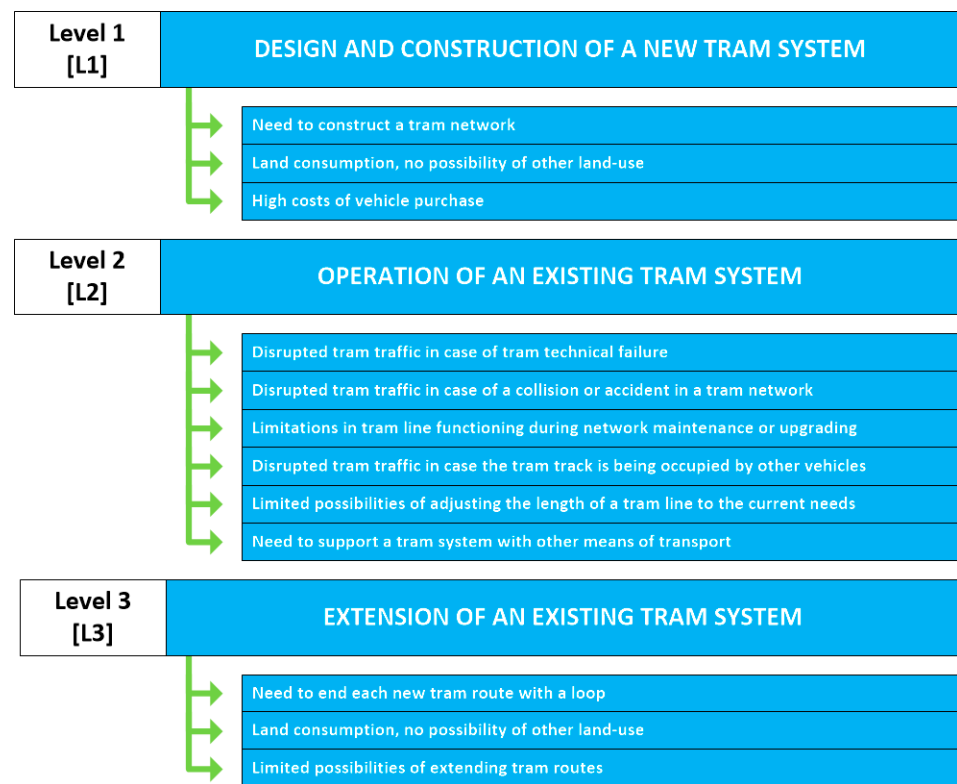


Figure 2. Uni-directional tram system limitations—results of the expert analyses.

As shown in Figure 2, the city tram system limitations defined by the expert panel were systematised and categorised into three levels of tram system functioning and development—L1, L2, and L3. Some of the identified limitations pertained to one level only, whereas others applied to more than one level. Detailed explanations of the individual limitations identified by the experts are listed below:

- **Need to construct a tram network (→L1)**

If a city has no tram system, but would like to have one, it would be necessary to design and construct the whole (linear and point) infrastructure dedicated to this means of transport, comprising tram tracks, tram loops, and tram depots, along with the indispensable technical facilities. This limitation is important to the extent that an analogical implementation of a bus public transport system in a city does not require construction of a full infrastructure network; a bus may use the public roads available in the city, so it is only necessary to construct bus loops and bus bays.

- **Land consumption; no possibility of other land-use (→L1, L3)**

A tram system infrastructure, with all its linear and point elements, takes up a certain amount of urban space. Due to the specific technical parameters of trams (e.g., turning radius), as well as legally stipulated technical requirements regarding tram infrastructures (e.g., the need to provide the minimum curve radiuses or minimum dimensions of tram loops), tram systems are more demanding in terms of space taken up than bus systems in cities.

A vital issue in designing and constructing a tram system is the need to provide sufficient space to locate the tram loops. In addition to the fact that it is necessary to find enough space for the tracks themselves, the area inside the loop cannot be freely developed.

Moreover, due to the design of a uni-directional tram, where the doors are located on the right-hand side of the vehicle, tram stops must be located on side platforms. However,

there may be some specific sections of tram routes where such tram stops cannot be designed; e.g., due to limited space available.

It should also be noted that space taken up by a tram infrastructure cannot be used for other purposes, or the uses may be very limited. Admittedly, some cities apply various solutions, such as traffic lanes shared by trams and buses or even passenger cars; however, this makes the tram vulnerable to traffic congestion, which leads to a decrease in its commercial speed, and consequently in its competitiveness in relation to individual transport.

- **High costs of vehicle purchase (→L1)**

In addition to the costs of the infrastructure, designing and implementing a tram system in a city also requires incurring considerable costs to purchase a specific number of trams. Naturally, developing a bus system in a city also involves the need to purchase a bus fleet; nevertheless, the price of a city bus is significantly lower than the one of a tram. In addition, it should be noted that the prices of individual means of transport may differ depending on the requirements of the ordering party. Tram manufacturers underline that they always adjust the vehicles to the requirements enumerated in the purchase order, taking into account the technical and legal possibilities. This has an impact on the final order price. When comparing the prices of trams and buses, it is also necessary to account for their capacity. Hence, the purchase price of a tram should be compared with that of a bus only when taking into account other factors.

- **Disrupted tram traffic in case of tram technical failure (→L2)**

A significant limitation of a tram system is the negative impact of a tram technical failure on the traffic of the other trams travelling in the network. Should one tram be immobilised within the network, the other trams have limited possibilities of movement, and the tram traffic may even be stopped at some point in the network. This is due to the fact that a tram permanently relies on the infrastructure (it can only travel on a track), so it is not easy (or sometimes it may be impossible) to pass an immobilised tram. In case of long-term hindrances in tram traffic, cities organise replacement service, usually engaging buses.

- **Disrupted tram traffic in case of a collision or accident in a tram network (→L2)**

Limitations of tram systems are also observed as a result of collisions or accidents taking place within tram networks, whether or not a tram is involved. In case of blocking the track by a damaged tram or car, the tram traffic is hindered or stopped within a specific part of the network. Similar to the case of tram technical failures, this is due to the permanent connection of the means of transport with the infrastructure, and consequently to the limited possibilities of getting ahead of the damaged tram or organising a detour.

- **Limitations in tram-line functioning during network maintenance or upgrading (→L2)**

In case of any maintenance or upgrading works involving a tram network, passengers normally using the tram services suffer inconveniences due to the limited availability of some tram routes. As a consequence of such maintenance or upgrading works, the routes of some specific tram lines need to be changed, and sometimes they must be totally suspended from passenger service. In practice, repairing even a small section of a given tram route makes it impossible for trams to get to the tram loop, thus preventing normal tram traffic.

Such a situation has an unfavourable effect on the possibilities of meeting the passengers' transport needs by the tram system, which many times forces city authorities to organise replacement service, usually engaging buses. Such decisions and solutions are aimed at mitigating the inconveniences suffered by passengers; however, this also forces them to change their transport-related behaviours and decisions.

- **Disrupted tram traffic in case the tram track is being occupied by other vehicles (→L2)**

Tram traffic disruption is observed not only in cases of technical failures, collisions, or maintenance/upgrading works. Tram tracks may be obstructed, e.g., by badly parked vehicles, which prevents trams from running. Similar to the case of the above-mentioned

situations, this is a serious limitation of a tram system: as opposed to a bus, a tram is unable to pass such a vehicle and must stop, which disrupts the traffic on the tram route.

- **Limited possibilities of adjusting the length of a tram line to the current needs (→L2)**

Planning a route for a tram line is dependent on having access to a tram loop. This means that any variations in a given tram line (e.g., additional services in peak hours covering short sections of tram routes) depends on the possibility of turning the tram around using another tram loop located on the route.

- **Need to support a tram system with other means of transport (→L2)**

One of the inherent features of a tram system is the reliance of the means of transport on its infrastructure. As a result, tram traffic may only be operated on tram tracks. Tram networks are limited in terms of size and range; they are developed mainly in traffic routes characterised by considerable traffic flows. Due to the above indicated limitations, tram systems need to be supported by other means of transport that perform the feeder function (bus transport, individual transport, and non-motorised transport (NMT)).

- **Need to end each new tram route with a loop (→L3)**

Possibilities of extending an existing tram system to provide new routes are limited by the need to construct a tram loop for turning around. Even though in some cases it is possible to combine a new route with an existing tram loop, it is still necessary to account for its maximum traffic capacity.

In accordance with the principle of technical indivisibility of transport infrastructure, investments in new tram routes must be carried out while ensuring the technical minimum, which is a prerequisite for safe and effective transport operation. Therefore, commissioning of a new tram route is dependent on having access to a tram loop. As tram traffic in both directions on a given route is predicated on the possibility of turning around at a tram loop, it is not possible to operate a section of a newly constructed route without a loop.

- **Limited possibilities of extending tram routes (→L3)**

If an existing tram route were to be lengthened, the extension would have to be ended with a tram loop. This entails specific consequences, such as a considerable increase in capital expenditures and the need to obtain a land plot to construct another tram loop. In addition, as the city expands, there may be no space for further, gradual extension of the tram route over time if needed.

The research study carried out using the Delphi method made it possible to provide a positive answer to RQ1 posed in the Introduction. The limitations of the uni-directional tram, as enumerated by the experts, were the starting point for carrying out an analysis of effects ensuing from applying bi-directional trams as a solution to improve the system functionality.

5. Bi-Directional Tram—The Idea and Effects of Its Application in a Smart and Sustainable City

5.1. Definition of a Bi-Directional Tram

Prior to defining the ‘bi-directional tram’, it is first necessary to identify the term ‘tram’ itself. According to a dictionary definition, a tram is ‘a passenger or freight road vehicle designed for operation on a tram line’ [119]. Pursuant to Regulation (EU) 2018/643 of the European Parliament and of the Council of 18 April 2018 on rail transport statistics, ‘a tram (streetcar) means a passenger road vehicle designed to seat more than nine persons (including the driver), which is connected to electric conductors or powered by diesel engine and which is rail-borne’ [120]. It should be noted that neither of the sources quoted above defined the term ‘bi-directional tram’. The nomenclature of the Polish legislation (Regulation of the Minister of Infrastructure of 2 March 2011 on the technical conditions for trams and trolleybuses and the scope of their indispensable equipment) defines a tram as ‘an electrically-driven vehicle designed for passenger or freight transport, running on rails on public roads’ [121]. What is important from the point of view of this article is that

the quoted legal act distinguishes between the two basic kinds of trams: uni-directional—described as a tram adapted for travelling in one direction, and bi-directional—described as a tram adapted for travelling in two directions.

In the authors' opinion, the cited definitions are not exhaustive in presenting the idea of the bi-directional tram as a means of transport; therefore, we proposed our own, extended definition. Namely, a bi-directional tram is a vehicle adapted for driving in two directions with duplicated equipment (two driver cabins and doors on both sides) that allows it to perform its function regardless of the direction of movement [94].

It should be noted that the parameters of the linear infrastructure applied in operating such a vehicle do not differ from the parameters of the linear infrastructure used by uni-directional trams. Differences in tram route design can be identified for tram stop locations and tram route terminals. In the case of a bi-directional tram, tram stops may be located both on the right- and left-hand sides of the tram; moreover, tram stops may be located in the space between the tracks of a double-track route. The difference in designing a tram route terminal for bi-directional trams lies in the fact that this type of vehicle is able to change the travel direction without the need to turn around at a tram loop; tram routes adapted for operation of bi-directional trams may be provided with switch-back terminals rather than tram loops.

5.2. Effects of Applying Bi-Directional Trams in a Smart and Sustainable City

As mentioned in the Introduction, this article aimed to determine what effects can ensue from applying a bi-directional tram in the context of the smart and sustainable city concept. Based on the results of the literature review and the research findings obtained using the Delphi method, the authors of this article analysed the effects of introducing the bi-directional tram as a solution to improve a tram system's functionality.

5.2.1. Reducing the Land Consumption of a Tram System by Applying Switch-Back Terminals at Tram Route Terminals

Our desk research showed that cities struggle with the problem of land consumption connected with transport development and subordinating the urban space to the needs of transport systems. As the experts pointed out, design, construction, and extension of a tram system that relies on uni-directional vehicles requires sufficiently large land plots to locate tram loops, which are indispensable for operating this type of tram. Application of a system based on bi-directional trams makes it possible to curb the land consumption; consequently, saved areas may be used for other purposes.

A bi-directional tram does not need a tram loop to turn around—it only needs a switch-back terminal (Figure 3). On the one hand, it enables the trams to change the travel direction; and on the other, it may serve as the location of the terminus. This is particularly convenient in a situation in which there is not enough space for a tram loop, or the space is planned to be used for other purposes.

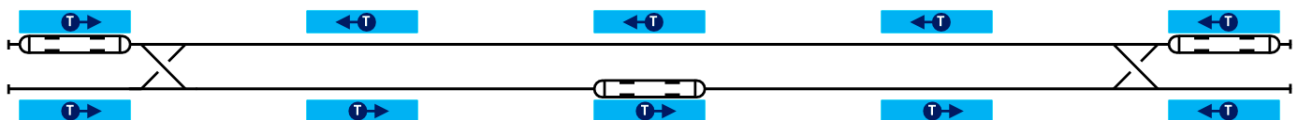


Figure 3. Operation of a bi-directional tram on a route with switch-back terminals at both ends of the tram route.

This solution resolves not only the problem of land consumption required by tram systems, but also provides a possibility of constructing tram routes in densely built-up or historic areas, as well as in the case of locating tram routes underground. Examples of applying this solution in various locations are shown in Figure 4.



Figure 4. Examples of tram route terminals without applying tram loops: (A) Alexanderplatz, Berlin, Germany; (B) Rogier, Brussels, Belgium; (C) Kanta, Olsztyn, Poland (own study).

In case there is no space for placing two tracks and a terminus at the switch-back terminal, it is possible to place a single track intended only for turning around and locate the tram stops before the switch-back terminal. An example of such an application is shown in Figure 5.



Figure 5. Terminating a tram route without applying a tram loop—Warsaw Street, Berlin, Germany: (A) own study based on openstreetmap.org; (B) own study.

5.2.2. Possibility of Commissioning Subsequent Sections of a Constructed Tram Route

Construction of a new tram route or extension of an existing one is cost-intensive and time-consuming. Commissioning such an investment may take place up to several years after commencing it.

Application of a bi-directional tram makes it possible to begin operation of subsequent sections of the tram route before the commissioning of the complete development project. It is enough to provide the end of the completed section with a switch-back terminal that will enable trams to change the travel direction (Figure 6). The last tram stop in this section will then serve as a temporary terminus. Thus, the subsequent route sections with subsequent stops may be gradually commissioned until the entire development project has been completed. What is important is that upon commissioning of another section of the route, the temporary terminal tracks of the previous section become the route tracks subject to regular operation. This solution may also be used in the case of staged development, depending on availability of funding.

In the case of a uni-directional tram, a newly built tram route may only be put into operation after the tram loop has been constructed. If any sections of the constructed tram route were to be commissioned before completion of the entire development project, this would require constructing a temporary (cost-intensive and land-consuming) tram loop. As a result, upon completion of the entire investment project, in addition to the indispensable

tram loops located at the beginning and end of the tram route, there would be redundant tram loops left within the route.

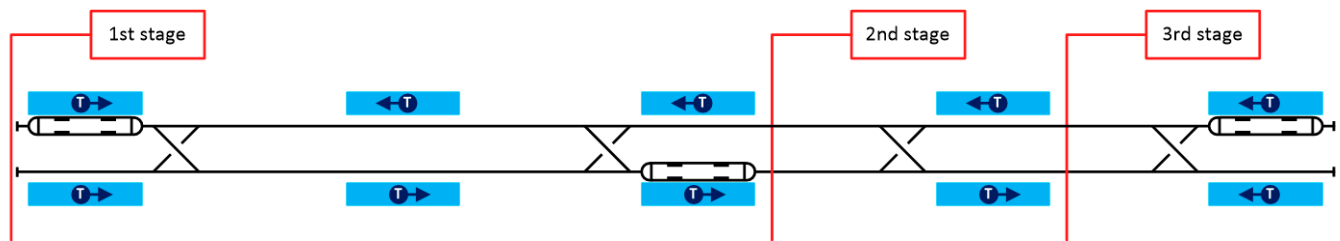


Figure 6. A bi-directional tram route commissioned in stages.

5.2.3. Possibility of Using Tram Stops Located Only on One Side of a Single-Track Line to Handle Passenger Flows in Two Directions

Limited space may be one of the reasons for constructing single-track routes. Application of uni-directional trams on such routes may be hindered. This is due to the need to locate tram stops on both sides of the track (as passengers may enter/exit from one side of the tram only) and to construct tram loops, which is land-consuming.

Application of bi-directional trams makes it possible to curb land consumption. Instead of tram loops at the ends of the route, switch-back terminals may be applied, while the possibility of letting passengers on and off from both sides of the vehicle allows the tram stops to be located on one side of the track only (Figure 7). In addition to that, if the space is extremely scarce, a single terminal track may be applied (without a switch-back terminal) and the bi-directional tram may be operated on a shuttle basis (Figure 8).



Figure 7. Using the bi-directional tram to serve tram stops located on one side of the track.



Figure 8. Using the bi-directional tram to serve a single-track tram route on a shuttle basis.

5.2.4. Possibility of Tram Line Shortening/Lengthening

When planning individual tram lines, a public transport authority must take into account both the needs of the city residents and the specific technical conditions of the tram system, such as a limited number of tram routes. In practice, this means that the individual tram lines in the city must share some sections of tram routes with other tram lines.

In the case of a uni-directional tram system, sharing specific sections of one route by multiple tram lines may also extend to their terminal sections, which is due to the need to ensure access of each tram to the tram loop (Figure 9). It is possible that the quantity of passenger-kilometres offered by the multiple tram lines on the shared (overlapping) end section of the route may considerably exceed the actual demand for transport. However, decreasing the service frequency of any of the individual tram lines would lead to a situation in which the decreased service frequency would affect the route sections served by single tram lines only.

Application of a bi-directional tram offers new possibilities, and its potential may be used to mitigate the limitations identified above. Application of a bi-directional tram eliminates the need for trams to turn around at a tram loop and provides a possibility of placing a switch-back terminal directly on the tram route, which makes it possible to diversify the routing of the individual tram lines on the shared sections of the route. In

this case, one tram line may serve the route up to the terminus located at the tram loop (Tram Line No. 1, marked in red in Figure 10), whereas the other tram line may serve up to the terminus located at the switch-back terminal (Tram Line No. 2, marked in green in Figure 10).

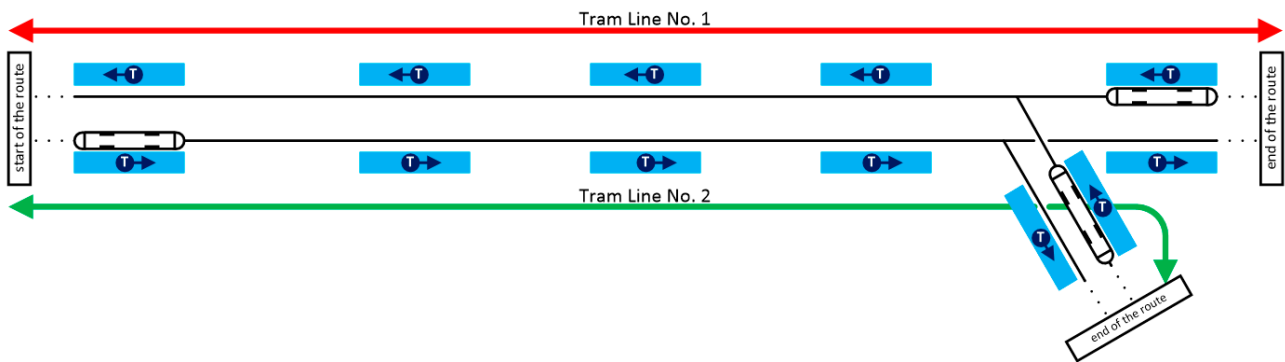


Figure 9. Sharing a section of a tram route by two sample tram lines.

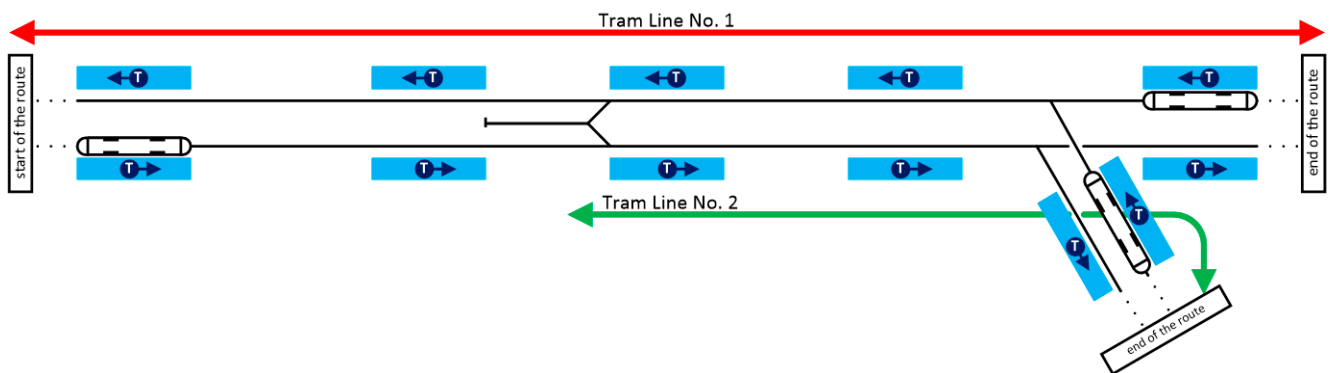


Figure 10. Using the bi-directional tram to diversify the routing of the two sample tram lines on the shared section of the route.

Another significant advantage of using a bi-directional tram in this aspect is the possibility of making changes to the routing of one tram line (shortening/lengthening) to account for any changes in transport demand resulting from, e.g., peak hours and mass or cyclical events. To attain this, it is necessary to construct additional switch-back terminals to serve as termini of the shortened tram line (Figure 11).

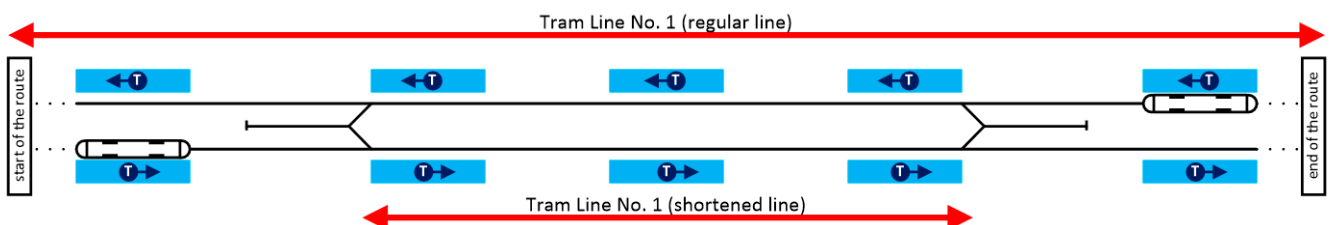


Figure 11. Using the bi-directional tram to diversify the routing of one tram line.

5.2.5. Possibility of Serving Tram Stops Located on Island Platforms

Sometimes, due to limited space, location of separate tram stops for each travel direction (on the outer sides of the tracks) may be hindered or impossible. A solution to this problem may be the application of one tram stop shared by both directions of the passenger traffic—an island platform (Figure 12). Island platforms may be served by bi-directional

trams. As a bi-directional vehicle is equipped with doors on both sides, it may also serve the passenger traffic on the inner side of the tracks.

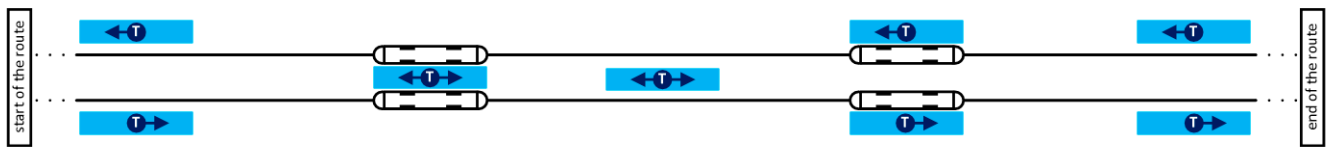


Figure 12. Using the bi-directional tram to serve tram stops located on island platforms.

It is worth noting that this type of stop may be located at integrated interchange nodes as one of the elements to support passenger traffic service. This solution also makes it possible for passengers to choose which side of the vehicle to exit, depending on their further travel plans; thus, they may exit at the stops located on the side platforms or island platforms (Figure 13).

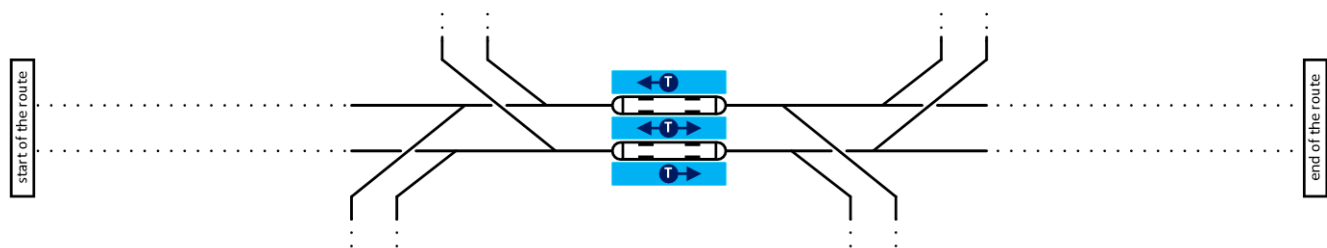


Figure 13. Using the bi-directional tram to serve tram stops located on side or island platforms.

5.2.6. Mitigating the Negative Effects of Maintenance/Upgrading Works on a Tram Network

An important task of any urban public transport authority is the need to ensure continuity of passenger service during any maintenance or upgrading work in the tram network. Such work results in a disruption of the continuity of the tram route, and consequently limitations in the traffic of specific tram lines.

If the network makes it possible for the tram line to reach the tram loop using another tram route, a detour is provided. In other cases, the given tram line is temporarily suspended, or its routing is temporarily changed (the tram line terminates at another tram loop). At the same time, in order to ensure passenger traffic continuity, replacement bus service is provided.

Application of a bi-directional tram enables mitigation of some negative effects of maintenance work carried out in the tram network. Placing a temporary switch-back terminal makes it possible to maintain the tram traffic on the maximum possible section of the tram route, excluding only the part of the track that is directly involved in the maintenance work (Figure 14). As a result, passengers still have access to tram services in the sections that are not covered by the maintenance work, and it is necessary to provide replacement bus service for a shorter section of the route.

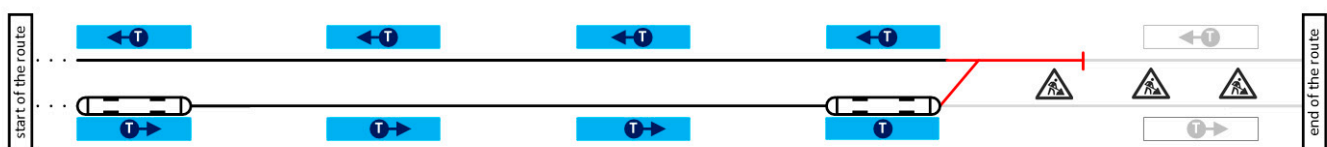


Figure 14. Using the bi-directional tram to serve a tram route in repair.

It is also worth noting that in order to mitigate the negative effects of maintenance work on the network, there is a possibility of performing them in two stages; i.e., closing one track at a time. Then the traffic may be handled on a shuttle basis using the available track.

Application of this type of solution in a uni-directional tram system enables the operators to maintain the traffic continuity; however, there is a problem with serving the tram stops. As uni-directional trams are adapted to serve tram stops located on side platforms (with doors on the right-hand side), they are able to serve the tram stops only when going in one of the directions. This is a significant inconvenience for passengers normally using the tram route, which frequently forces them to change their transport-related behaviours (e.g., choosing another stop or another means of public transport, or choosing individual transport).

In the case of bi-directional trams that have doors on both sides, it is possible for them to serve the stops located on the temporary single-track route regardless of the travel direction, which enables all passengers of the tram line to continue using the tram services.

5.2.7. Mitigating the Negative Effects of Technical Failure/Collision on a Tram Network, or of Track Obstruction by Other Vehicles

The permanent connection between the means of transport and the infrastructure, which is the feature of tram transport, has its consequences. One of them is setting up detours, which may be hindered or even impossible (depending on the tram network layout and the number of tram loops). Tram system operation is often disrupted by blockage of the track (e.g., due to tram technical failure, collision of vehicles on the track, or obstruction of the track by other users of city transport), which causes a disruption in the tram traffic and thus passenger service. In this situation, uni-directional trams usually wait on the track until the traffic can be restored, which may lead to delays, car traffic hindrances, and in some cases even total suspension of the tram traffic on the given tram line(s).

Application of bi-directional trams may to a certain extent curb the above-mentioned problems. Due to its duplicated equipment (two driver cabins), a bi-directional tram may safely travel in the opposite direction without the need to turn around at a tram loop. Due to this property of bi-directional trams, the traffic management entity may, e.g.:

- Withdraw the queuing trams to the route terminus in order to decongest the traffic;
- Arrange the tram traffic on a temporarily shortened tram route using the available switch-back terminals (see Sections 5.2.2 and 5.2.4).

Such activities may contribute to clearing up the tram traffic.

The completed analysis made it possible to identify the effects that may result from the introduction of bi-directional trams in cities, which was the subject matter of RQ2.

6. Practical Aspects of Using Bi-Directional Trams in the Public Transport System in Szczecin, Poland—A Case Study

6.1. Public Transport in the City of Szczecin, Poland

The city of Szczecin is located in the northwest of Poland. It is the largest city in that part of Poland, both in terms of the surface area (301 km² as of 30 June 2021) and the population size (395.5 thousand as of 30 June 2021) [122]. Szczecin is also the capital city of the West Pomerania Voivodeship and the key urban centre of the Szczecin Metropolitan Area (SMA). Its area also contains one of the key Baltic seaports, and the following international transport routes run through Szczecin: roads E28 and E65 and railroads E59 and CE59.

The entity responsible for public transport in Szczecin is the Roads and Public Transport Authority (RPTA), which acts on behalf of the Szczecin municipality. The city's public transport comprises bus and tram services. The transport services are performed on the basis of agreements reached by the RPTA with one public tram operator (Tramwaje Szczecińskie Sp. z o.o.) and four public bus operators (Przedsiębiorstwo Autobusowe 'Klonowica' Sp. z o.o., Szczecińskie Przedsiębiorstwo Autobusowe 'Dąbie' Sp. z o.o., Szczecińsko-Polickie Przedsiębiorstwo Komunikacyjne Sp. z o.o., and Przedsiębiorstwo Komunikacji Samochodowej w Szczecinie Sp. z o.o.) [123]. It is worth noting that in the future, the Szczecin Metropolitan Railway is planned to be put into operation—however, it will cover the area of the SMA, which goes far beyond the boundaries of the city of Szczecin.

As of 2022, the passenger public transport in Szczecin comprised 96 various bus or tram lines, including:

- 11 daytime normal tram lines;
- 63 daytime normal bus lines;
- 2 daytime normal bus lines—transport on demand;
- 2 daytime fast bus lines;
- 2 replacement bus lines (operated instead of tram lines during times of tram network maintenance in Szczecin);
- 16 night bus lines.

In view of the objective of this paper, the object of further analysis was the tram system functioning in the city. According to the data obtained from the tram operator as of 31 December 2021, the tram infrastructure in Szczecin comprised 126 km of tram tracks, of which 116 km were used in passenger transport. Each tram route is adapted for operation of uni-directional trams and terminates with a tram loop. There are 13 available tram loops in the city. It should be noted that there are no routes adapted exclusively for bi-directional trams; i.e., terminating with switch-back terminals. Two tram depots are responsible for operation and maintenance of trams in the city.

According to the data as of 31 December 2021, the tram fleet in Szczecin comprised 199 vehicles, of which 197 were uni-directional, and only 2 were bi-directional (both of which were purchased in 2020–2021). Currently, both bi-directional trams are used in passenger transport only in the uni-directional tram operation mode—each time they use a tram loop to turn around. It is worth noting that as the city develops and expands and as the city authorities make investments in the tram system, the features of bi-directional trams provide opportunities to build smart and sustainable urban public transport.

6.2. Examples of Practical Applications of Bi-Directional Trams in Szczecin, Poland

The tram system in Szczecin has been operating for many years, therefore the analysis of practical applications of bi-directional trams only covered the two levels established in the survey carried out by means of the Delphi method: L2—operation of an existing tram system, and L3—extension of an existing tram system.

A vital problem currently faced by the transport system of Szczecin is upgrading the tram network. According to the results of the Delphi study, maintenance work may lead to significant inconveniences for passengers resulting from the need to change the routing of individual tram lines or their temporary suspension. Currently in Szczecin, there is a process underway that stipulates the upgrading of as many as 26 km of tram tracks. What is important is that these are mostly tram route sections located in the city centre that are normally used by multiple tram lines. For example, tram traffic at one of the major public transport nodes (Plac Rodła) has been totally suspended, while normally as many as seven tram lines run through that point, namely: 1, 2, 3, 5, 10, 11, and 12. Additionally, due to the pending upgrade process, two tram loops have been taken out of operation, which led to total suspension of tram traffic around the main railway station in Szczecin, where normally tram lines 3 and 6 operate. This means that as a result of the upgrading works currently carried out in Szczecin, out of 12 tram lines, only 3 are operating without any changes (tram lines 7, 8, and 9). During times of the maintenance work, one tram line has been totally put out of operation (tram line 4), whereas as many as eight tram lines have had their routes changed (tram lines 1, 2, 3, 5, 6, 10, 11, and 12).

Figure 15 presents a ca. 1 km long section of the tram route between Plac Szarych Szeregów and Plac Rodła (along Marszałka Józefa Piłsudskiego Street). Even though the 0.85 km long section of the track (marked blue in part A of Figure 15) together with two tram stops normally used by tram lines 1, 5, 11, and 12 could be operated, they were out of operation due to maintenance work carried out at the Plac Rodła transport node.

As shown in Section 5.2.6, an important aspect of applying bi-directional trams is the possibility of mitigating some negative effects of maintenance work being carried out in the tram network. Part B of Figure 15 shows the proposed location of a temporary switch-back

terminal. Until the end of the maintenance work, it could serve as the terminus for any selected tram line(s), making it possible to transport passengers as far as to Plac Rodła. Applying this solution would make it possible to maintain the continuity of the tram traffic on a 0.85 km section of the route and to serve two permanent tram stops (Plac Szarych Szeregów and Plac Grunwaldzki), as well as an extra temporary tram stop located at the temporary switch-back terminal at Plac Rodła. As a result, the walking distance for tram passengers would be only 150 m instead of 1 km. Moreover, it is worth noting that this solution is particularly important for people suffering from mobility limitations, for whom suspension of the tram services over the length of as much as 1 km may lead to a total inability to move around the specific area.

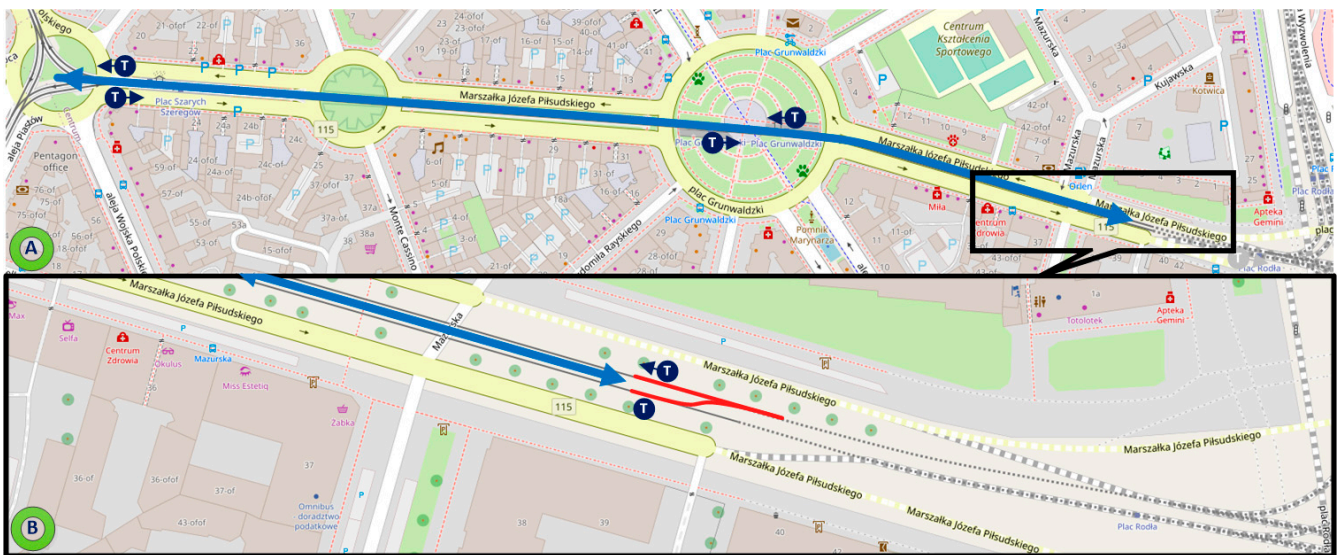


Figure 15. Using the bi-directional tram to serve the passenger traffic on the tram routes being upgraded in Szczecin (own study based on openstreetmap.org).

In addition to the current maintenance of the tram network, the city is also planning the system extension. One of the pending projects will extend the tram route located in the western part of the city, in the district of Gumieńce. The project stipulates extension of the existing route by ca. 0.9 km and construction of a new tram loop located along Ku Słońcu Street, directly along the administrative boundary of Szczecin. The new tram loop will increase the availability of tram services for residents of the new residential developments, as well as those located outside the city's boundaries. The tram route proposed by city authorities and the planned location of the tram loop are shown in part A of Figure 16.

In the context of this public transport development project, there is one more issue worth considering. Namely, the tram route extension also is aimed at improving the availability of the tram network for multimodal journeys. Therefore, it seems reasonable to provide that area with commodious car lots, such as Park & Ride (P&R) and Bike & Ride (B&R), along with the possibility of short-term parking—Kiss & Ride (K&R). Unfortunately, the tram loop design exposes a considerable extent of land consumption, and hence no possibility of constructing the above-mentioned car lots.

A vital effect of applying bi-directional trams in the contemplated development project is a considerable reduction in the land consumption as a result of locating a switch-back terminal at the end of the tram route (part B of Figure 16). Application of this solution would make it possible to 'release' almost 9000 m² of the grounds. Thus, saved land may be used for construction of a spacious P&R car lot along with B&R and K&R areas, which would have a positive effect on improving the accessibility of public transport for people affected by mobility limitations. It should also be stressed that in view of the densely built-up residential area, the existing tram loop in the Gumieńce district offers a mere 14 parking

spaces, of which only 1 is reserved for people with disabilities. It is also important that terminating the tram route with a switch-back terminal can make it easier to further extend it in the future and thus improve the public transport availability for several thousand residents of the farther-located housing developments.

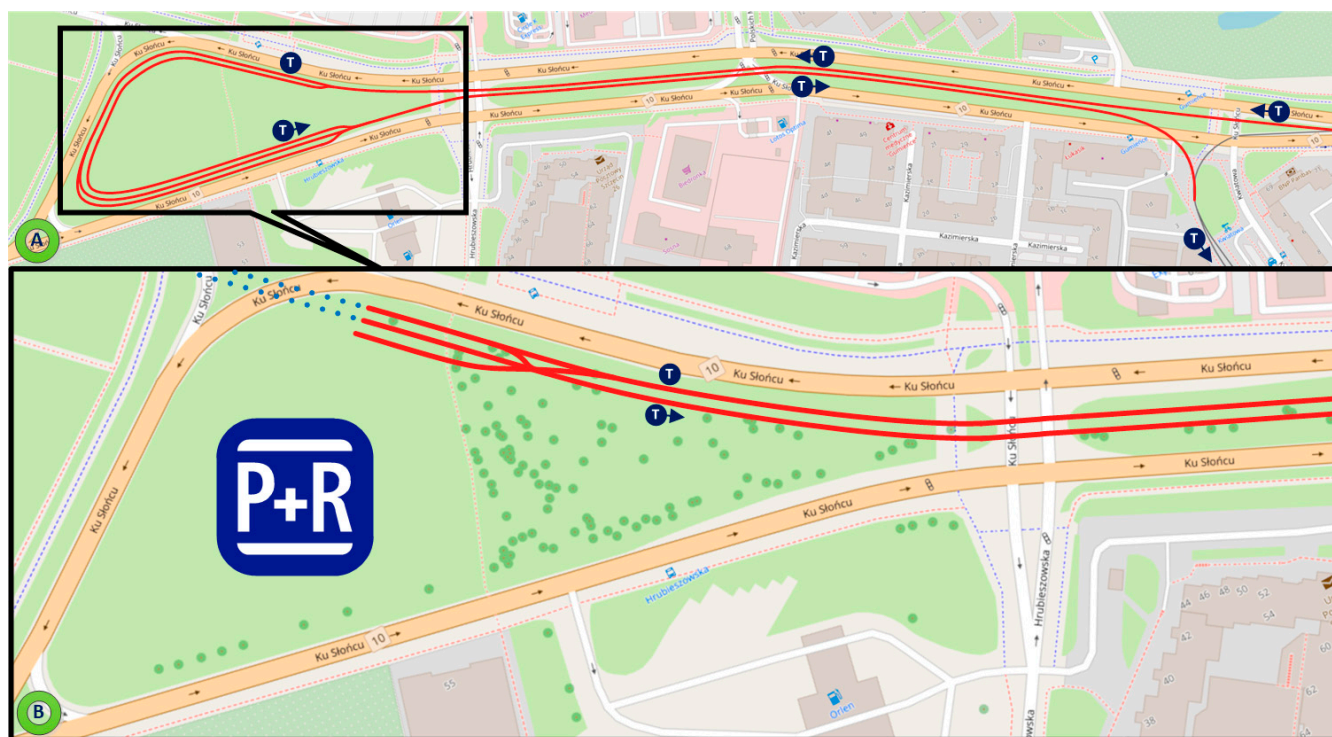


Figure 16. Application of the bi-directional tram as an alternative approach to the development project (tram route extension in the Gumieńce district in Szczecin) (own study based on openstreetmap.org).

Another investment project planned by city authorities is construction of a new tram route ca. 4.9 km in length running between Bohaterów Warszawy Street and the Krzekowo tram loop on Żołnierska Street (the planned route is marked in red in part A of Figure 17). Meanwhile, the Krzekowo tram loop is to be removed, and the route is to be extended for another 0.8 km (the route is marked in green in part A of Figure 17) to terminate with a new tram loop to be located on Władysława Szafera Street. Following the completion of the development project, the new route is to be used by tram line 13 and run from the main railway station to the said tram loop.

Due to the scope of work and the planned route length, the investment project requires a considerable capital expenditure, which may lead to shelving the project for later. In addition, its commissioning may be postponed—when uni-directional trams are used, it is necessary to complete the entire route together with the tram loop.

In the case of this project, application of bi-directional trams may also result in measurable benefits, as the development project might then be divided into two phases:

- Phase I—completing the ca. 2.4 km long section of the route and terminating it with a switch-back terminal (marked in red in part B of Figure 17);
- Phase II—completion of the remaining section (ca. 2.5 km in length) and terminating at the existing Krzekowo tram loop.

Completion of the first phase of the development project will make it possible for tram line 13 to begin operation from the main railway station to the temporary terminus located at Osiedle Kaliny. What is important is that the commissioning of tram line 13 will make it possible to relieve (or maybe even withdraw from service) bus line 75, as both lines overlap. Thus, application of bi-directional trams will make it possible to operate the specified route

section as soon as Phase I has been completed, and without the need to construct the route section covered by Phase II.

Using bi-directional trams on this tram line may also bring an additional benefit. The tram route running through the main railway station in Szczecin is normally used by two tram lines (3 and 6). The terminus of both lines is located at the Pomorzany tram loop, ca. 2.6 km away from the railway station. If bi-directional vehicles were used, the new tram line 13 could terminate in front of the railway station, without the need to overlap with tram lines 3 and 6 between the railway station and the Pomorzany tram loop. This solution would make it possible to shorten the tram line route by as much as 2.6 km in one direction (the distance to be covered by the uni-directional tram only to be able to turn around at the tram loop) and 5.2 km in both directions for just one tram. For each 24 h time span, application of bi-directional trams would make it possible to reduce the number of redundant kilometres by 468 ($90 \text{ cycles per } 24 \text{ h} \times 5.2 \text{ km/cycle} = 468 \text{ km/24 h}$). In addition to that, operating the shortened line with bi-directional trams would require only five vehicles, whereas as many as seven vehicles would be needed if uni-directional trams were used. What is important is that the configuration of the tram tracks in front of the railway station already makes it possible for trams to change the travel direction without the need to turn around at a tram loop (marked in red in Figure 18).

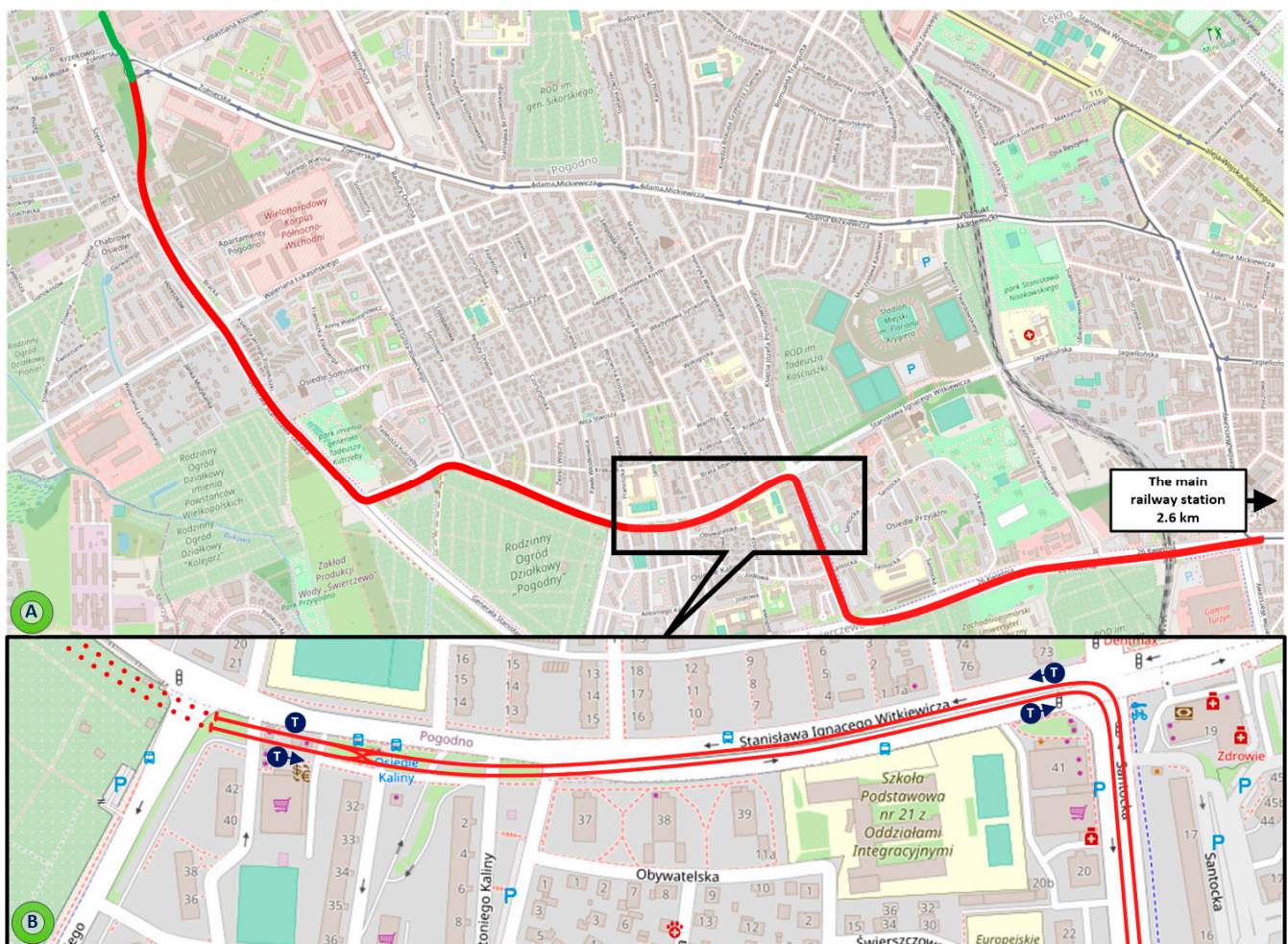


Figure 17. Application of the bi-directional tram, enabling phased development (construction of the tram route to the Krzekowo tram loop on Żołnierska Street in Szczecin) (own study based on openstreetmap.org).

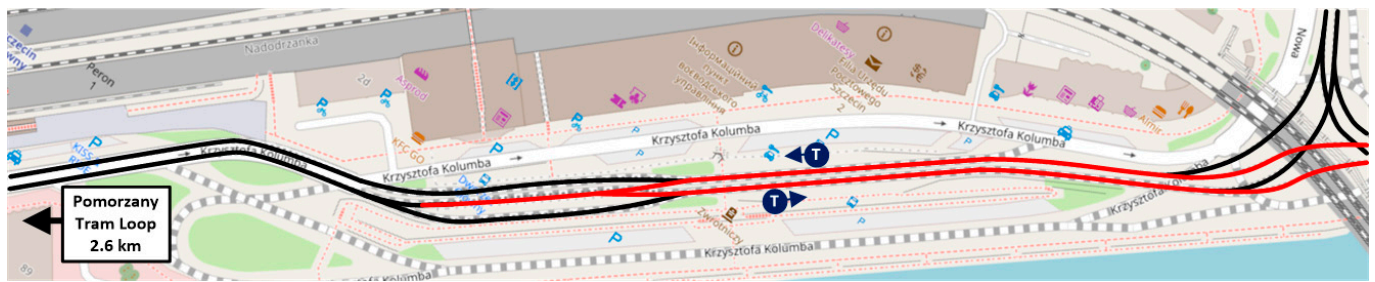


Figure 18. Application of bi-directional trams on tram line 13 using a switch-back terminal in front of the main railway station in Szczecin (own study based on openstreetmap.org).

Another example of a practical application of bi-directional trams in Szczecin may also be the construction of a single-track tram route between Plac Grunwaldzki and the Szczecin City Hall (SCH). As this is a densely built-up historical area, there is not enough space to accommodate a tram loop or a double-track tram line. What is more, there is no space for locating tram stops on both sides of the track, which excludes the option of using uni-directional trams.

The advantage of bi-directional vehicles in this case is the possibility of constructing a single terminal track (without a switch-back terminal) and operating the trams on a shuttle basis, where the tram stops would be located on one side of the track only and used by passengers going in either direction (Figure 19).

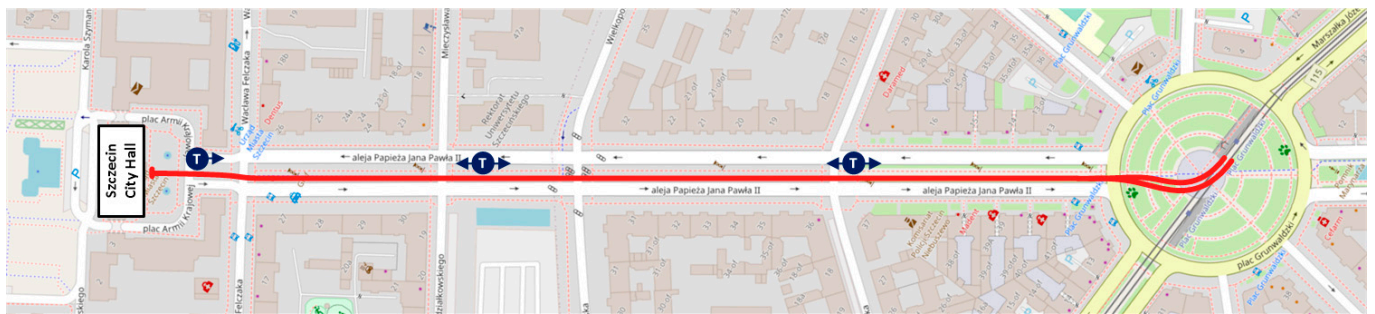


Figure 19. Application of bi-directional trams to operate a single-track tram line running to the Szczecin City Hall (own study based on openstreetmap.org).

It should be noted that the SCH generates significant passenger traffic, which intensifies the passenger car traffic in that area. Providing a tram line may result in a takeover of the existing passenger flows by sustainable public transport.

Additionally, in accordance with the numerous studies in that respect [108,109], as a result of construction and operation of a tram system, the city could gain a potential marketing effect. This is because cities with tram systems tend to be perceived as attractive and modern. If a new tram line is launched to run to the seat of the city's authorities, this may be viewed as a validation of the city's striving to implement the smart and sustainable city concept.

The possible practical applications of bi-directional trams in Szczecin (Poland) indicated in this section prove that a bi-directional tram may be an effective tool in improving the functionality of a tram system in a city. This provides a positive answer to RQ3 posed in the Introduction.

7. Discussion

In response to the identified literature gap, a research study was carried out with regard to tram system limitations and possibilities of improving the tram systems functionality.

Based on a case study of the city of Szczecin (Poland), practical aspects of bi-directional tram application in that city were identified, along with the expected effects.

According to the results of the Delphi study, a uni-directional tram system has its specific functioning limitations. Taking into account the properties of bi-directional trams, an analysis was carried out to examine possibilities of improving the system functionality via implementing this type of vehicle in the city's tram system. The results showed that the proposed solution may contribute to total or partial elimination of most of the limitations identified by the experts. Hence, introduction of bi-directional trams may contribute to, *inter alia*:

- Reduction in the land consumption by the tram system via applying switch-back terminals instead of tram loops, and also providing the possibilities of operating single-track tram lines and serving tram stops located on island platforms;
- Utilising the land saved as a result of reducing the land consumption by the tram system for other city-planning purposes;
- Curbing some inconveniences that arise during tram technical failures, collisions, and accidents in the tram network, or obstruction of the track by other vehicles, which is possible due to the tram's ability to move in the opposite direction without the need to turn around at a tram loop;
- Curbing some inconveniences that arise during any maintenance or upgrading works carried out in the tram network by providing a possibility of sustaining the tram traffic along the maximum possible lengths of the tram route;
- Adapting the tram lines to the current needs (shortening or lengthening of tram lines);
- Phased construction of a tram route and commissioning its subsequent sections prior to completion of the entire project.

Obtaining the effects enumerated above ensuing from application of bi-directional trams may contribute to the improved functionality of a tram system as an aspect of the smart and sustainable city concept.

Nevertheless, introduction of bi-directional trams will not solve all limitations of a tram system. Admittedly, having a tram system entails the need to construct a tram network while incurring significant capital expenditures to purchase the vehicles, as well as the need for a tram system to be supported by other means of transport; however, these constraints regard both uni- and bi-directional tram systems. Nonetheless, it is worth noting that:

- Application of bi-directional trams makes it possible to eliminate the need for tram loops, which significantly reduces the scope of such development projects;
- Even though the tram purchase cost may be high, the service life of this means of public transport is significantly longer and its passenger capacity is considerably larger compared to buses;
- In turn, the need for a tram system to be supported by other means of transport is an effect of the inherent feature of rail-borne transport; i.e., the permanent reliance of the means of transport on the infrastructure and the ensuing limited possibility of working on a door-to-door basis.

However, a well-designed tram system along with NMT and a bus system supporting it with feeder connections may provide effective passenger transport for a city, in accordance with the smart and sustainable city concept.

When analysing the results of the research, it should be stressed that the application of bi-directional trams in a smart and sustainable city may be effected by different variants. One of these is the design, construction, and extension of a tram system based exclusively on bi-directional vehicles (homogeneous system). As the infrastructure for such a system does not need to be adapted for uni-directional tram operation, any future upgrading works may be performed while accounting for the possibilities offered by bi-directional vehicles. An example of a city that introduced this solution is Olsztyn, Poland.

Another variant may be the introduction of bi-directional trams to an existing uni-directional tram system and operating them (mixed system). In this case, depending on the

investment-related decisions made by city authorities, bi-directional trams operate on the infrastructure adapted exclusively for uni-directional vehicles, or on a mixed infrastructure that provides both tram loops and switch-back terminals. Any upgrading work in that system may also be carried out while making use of the possibilities offered by bi-directional trams. This solution was chosen and implemented by Polish cities such as Poznań, Wrocław, and Warsaw.

It should be noted that the specific nature of the proposed solution makes it possible for both types of trams to be used on a complementary basis or to phase the uni-directional trams out and replace them gradually with the bi-directional ones. It is important that, in order to obtain positive effects, it is enough for city authorities to take evolutionary rather than revolutionary measures. This is because a vital strength of a bi-directional tram is that it has all the advantages of a uni-directional vehicle, so it may also be used in exactly the same way. Therefore, the bi-directional tram is more universal compared to the traditional one.

8. Conclusions

The smart city concept originated as a solution to improve sustainability and liveability of cities through effective management, energy, and transportation [124]. A significant challenge for smart cities faced by the progressing urbanisation and the growing need for transport services is a shift to green, safe, and sustainable means of transport [125]. Their key task is to provide their residents with appropriate conditions for smart mobility.

In view of its commercial speed and passenger capacity, tram transport may be a very efficient element of a city's transport system [126]. For that reason, it may be a vital component of smart and sustainable urban public transport. Unfortunately, issues related to tram system functioning have not been addressed by researchers to a sufficient extent. Therefore, the authors of this article engaged in a research study aimed at identifying the effects of applying bi-directional trams as the aspect of the smart and sustainable city concept. The research results enabled formulation of the following conclusions:

1. A uni-directional tram system, despite its significant benefits (electromobility, considerable capacity, and commercial speed) features a number of limitations in terms of its functionality.
2. There are effective tools for improving a tram system functionality in a city. One of these is the application of bi-directional trams.
3. Introduction of bi-directional trams may result in sizeable benefits for the city and its residents.
4. Implementation of bi-directional trams represents a chance to raise the attractiveness of a city's public transport, which is a major challenge for smart and sustainable cities.

The results obtained from this research study have both theoretical and practical implications. The theoretical aspect of the research pertained to filling the identified literature gap in the area of tram system limitations and possibilities of improving tram system functionality. The practical aspect of the research pertained to the possibility of the implementation of its results by local governments, public transport authorities, and tram operators in the process of designing new tram transport systems, as well as operating existing ones, in order to improve their functioning. The described case study based on the example of the city of Szczecin showed that implementation of bi-directional trams may bring measurable benefits. The solutions analysed in Szczecin include, i.a.:

- Maintaining the continuity of the tram traffic over the 0.85 km section of the route, serving two permanent and one temporary tram stops during the repair of the Plac Rodła transport node;
- Shortening the walking distance (to be covered during the repair of the Plac Rodła transport node by tram passengers) from 1 km to 150 m, which is particularly important for people suffering from mobility limitations;
- 'Releasing' almost 9000 m² of the grounds in the Gumieńce district, which may be used to construct P&R, B&R, and K&R car lots and parking spaces for people with dis-

abilities, thus improving the availability of the tram network for multimodal journeys for several thousand residents of the farther housing developments (also those located outside the city's boundaries);

- Shortening the route of tram line 13 by 2.6 km in one direction (5.2 km in both directions) per vehicle, which would make it possible to reduce the number of redundant kilometres by 468 per 24 h and to reduce the number of operated vehicles from seven to five.

It should be stressed that in view of the intensive development of the smart and sustainable city concept, it is important to search for other solutions aimed at improving tram system functionality as a tool for raising the attractiveness of public transport. This aspect will be the subject of further studies.

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