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# DEVELOPING NEW URBAN RAIL TRANSPORT IN MID-SIZED CITIES – A CASE STUDY OF RZESZOW, POLAND

**Summary.** The "renaissance" of urban rail transport as a means of efficient and sustainable urban mobility systems is an increasingly popular theme in mid-sized cities. However, such cities often grapple with the uncertainty of new public transport (PT) modes' effectiveness, which requires proper analytical underpinning. In this study, we assess the implications of introducing a new light rail (LRT) vs. heavy rail (HRT) transport solution in the case study city of Rzeszow, Poland, using transport simulation and accessibility models. The results reveal a more advantageous performance of an LRT-based tram system, whose benefits are enhanced by reduced road capacity in the city center and long-term shifts in mobility behavior. Ultimately, the PT capacity utilization with LRT improved by 12%, PT modal share rose from 28% to 35%, and inner-city car traffic loads declined by 20%. Our findings reaffirm that in concentric, mid-sized cities such as Rzeszow, urban rail transport should be based on a high-coverage, high-frequency LRT (e.g., tram) mode, which can form an effective backbone of the city PT system. Our study contributes to research on how new urban rail systems can help reverse the decline of PT ridership and facilitate the sustainable urban (re)development of mid-sized cities.

## 1. INTRODUCTION

Public transport (PT) development is commonly perceived as critical to ensuring efficient and sustainable urban mobility services. Today, a growing variety of urban PT services and sub-modes are feasible, from conventional mass-transit systems (buses, trams, trains) to contemporary demand-responsive and paratransit solutions enabled by technological advancements. Selecting the most appropriate PT solution is a common and crucial dilemma in long-term transport planning strategy, with various solutions and approaches pursued in cities worldwide.

Among these, an increasingly observable trend is the so-called urban rail transit renaissance [1–2]. Rail-based systems are noted for their advantages, including their high passenger capacity, high operational speeds, strong travel time reliability, resilience to both exogenous and endogenous disturbances (e.g., road traffic congestion, bus bunching), and traffic safety gains. Especially in large cities and metropolitan areas, they provide more effective passenger throughput at lower operational costs [3]. New tramway or metro projects are often intertwined with wider urban regeneration schemes, contributing to the perceived attractiveness of urban realm quality and tangible socio-economic benefits (population growth, stimulated economic activity, land value uplift, social equity, and inclusiveness)

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[4–5]. Moreover, given modern-day climate adaptation challenges, rail systems offer the most environmentally friendly and energy-efficient mass transportation services [6–7]. Empirical evidence shows that cities with new (or expanded) rail systems achieve extra congestion and pollution mitigation benefits (on average) by up to 10%, which tend to increase in the long term [8]. Though such gains are especially notable in high-population metropolises, they are also relevant in mid-size European cities.

The rail-based PT systems can be divided into two principal categories: **light rail transit (LRT)** and **heavy rail transit (HRT),** whereby a crucial demarcation criterion is the quality of rights-of-way [9–10]. The general consensus is that *LRT* refers to rail systems that preferably utilize designated rights-of-ways, yet they may also operate in mixed-traffic conditions with extensive signaling priority at intersections. A common example of an LRT is the tramway system, for which tram tracks run on street level but often along designated traffic lanes or separately from the road carriageway, and tram operations are managed by signaling priority based on intelligent transportation systems (ITS). The HRT concept corresponds to a rail system with its own distinct rights-of-way, which are grade-separated from other transport modes. Typical HRT solutions comprise (sub)urban rail systems, which operate above ground and/or underground, with trains of a larger passenger capacity or, less commonly, an (overhead) monorail system. The LRT system is typically less cost-intensive and is characterized by more convenient on-street accessibility; however, compared to HRT solutions, it also features lower passenger throughput and operational speeds [11].

The proper and cost-effective design of an urban rail system poses an important challenge, particularly for mid-sized cities. Passenger rail schemes are often subject to intense debate on whether substantial investment (and maintenance) costs will be used based on eventual socio-economic benefits [12]. In contrast to larger metropoles, where the debate revolves around what LRT and/or HRT system should be developed, mid-sized cities (i.e., with a population of 100,000–500,000 inhabitants) face the dilemma of whether they can afford a new urban rail solution at all [13]. In many cases, a well-designed bus priority system can be the only cost-effective solution under lower demand intensity, especially for short-distance trips. The literature suggests that the threshold city population of approx. 300,000 is a rough benchmark for attaining LRT effectiveness [14], yet this can vary substantially depending on the specific case. In fact, ca. 20% of LRT systems worldwide are estimated to operate in cities with populations under 200,000 [14].

The LRT (or sometimes even HRT) can be a justifiable solution in the context of travel density in specific corridors or city areas. Empirical evidence from the UK cites a threshold of approx. 2,500–4,000 passengers per hour per direction, where the long-term cost-benefit ratio of the LRT system becomes comparable with that of a bus service [11]. This can be further legitimized if crowding externalities are accounted for in the high-demand travel corridors [15]. Moreover, tram- and LRT-based solutions are more flexible in mid-sized cities and can operate effectively under relatively lower demand conditions [11], whereas the HRT systems require higher peak passenger flows, achieving at least 10,000–15,000 passengers per hour [16].

Finally, there is evidence to suggest that LRT projects have a significant and positive influence on travel behavior and PT usage in mid-sized cities. In several British and Polish cities, the newly (re-)introduced LRT systems are estimated to have attracted approx. 20–30% of their ridership is from car transport, both during peak periods as well as for weekend trips [2, 11]. These LRT services have increased trip frequency, travel comfort and accessibility, and reduced journey times, especially along main travel axes to/from the city center. As such, the new LRT systems in mid-sized cities are a major contributor to the perceived attractiveness of urban PT systems [2].

Despite numerous studies and practical advancements, many mid-sized cities encounter barriers with regard to the development of new urban PT systems. High investment costs and uncertain ridership forecasts are the main hindrances of urban rail investment [17]. While state-of-the-art provides a useful analytical toolset in that regard, its methods and conclusions are often confined to theoretical models or individual (case-specific) applications. Hence, an in-depth analytical underpinning is crucial to justify future PT development in mid-sized cities. This necessity includes simulation models of real-world PT networks, reproducing the wide range of interactions between transportation demand and supply [18]. Such models can capture the elasticity effects of passenger demand with respect to supply changes (e.g., new PT services, resultant travel time changes) and, consequently, forecast the potential LRT or HRT ridership with regard to long-term changes in land use, travel behavior, etc.

This study focuses on the simulation-based analysis of introducing a new urban rail transport system in a mid-sized city. Two various solutions are proposed as the "new" core of the city PT network: a corridor-based HRT system with higher operating speeds versus a grid-based LRT network of higher accessibility. We utilized multi-modal transport modeling to forecast passenger flows and evaluate travel-related parameters in various scenarios, complementing them with accessibility analyses based on GIS (Geographic Information Systems). Case study analyses for the city of Rzeszów, Poland (approximately 200,000 inhabitants), highlight the prospective effects of monorail (HRT) versus tram (LRT) solutions. Furthermore, the study outcomes demonstrate the potential synergy of new PT schemes with additional measures, such as road capacity reduction and changes in mobility behavior.

In this study, we aimed to contribute to the current understanding of developing effective PT systems in mid-sized cities. In contrast to major metropolitan areas, such cities often face the dilemmas of expanding the conventional PT network and reversing the vicious cycle of deteriorating PT ridership and operational efficiency. Based on the case study of Rzeszow, our insights show whether (and what) new rail-based systems can help address such concerns in mid-sized cities. The grid-based LRT tram system seems better positioned to efficiently serve everyday mobility needs. The HRT-based monorail system, while also being a positive solution, does not achieve as advantageous or breakthrough results. The findings of our research highlight the potential for sustainable and effective urban rail transportation systems, whose development is much-needed in multiple mid-sized cities.

The remainder of this paper is organized as follows. Section 2 provides a summary description of the case study city of Rzeszow and its present-day PT system. Section 3 presents the analytical methodology, comprising multi-modal transport models and GIS-based accessibility analyses. Section 4 follows with an in-depth analysis of the study results. Section 5 wraps up this study with a summary of the findings, implications, and future research directions.

## 2. CASE STUDY – CITY OF RZESZOW, POLAND

**Rzeszow** (in Polish: **Rzeszów**) is a mid-sized city situated in the southeast of Poland. Official figures for the year 2021 [19] showed a city area of 128.5 sq. km and a population density of 1545.5 pers./sq km. The registered population was approx. 198,600 inhabitants (the 15th most populous city in Poland), though it is estimated that the city's transport system is used by over 250,000 people on a daily basis.

The modern city structure has evolved largely in a concentrated manner, with urban development mostly situated within (or along) the city ring road area. However, the impacts of suburbanization and urban sprawl have recently gained momentum, putting additional strain on the city transport system. New housing and workplace developments in suburban Rzeszow areas may not be highly accessible via the current bus network. Consequently, the rising popularity of car travel has been witnessed in recent years, intertwined with greater road traffic congestion in peak periods.

City policymakers have thus begun to consider major improvements to the existing bus network [20], as well as the introduction of a new, rail-based PT system. Among the proposals, the on-street tramway network (akin to LRT standards) and/or the traffic-separated monorail system (more in line with HRT standards) have been conceived as two potentially effective solutions to the emerging mobility challenges in Rzeszow. Little analytical work has hitherto been conducted on the prospective efficacy and relative advantages or shortcomings of these different urban rail systems.

### 2.1. Existing public transport (PT) in Rzeszow

The PT system in Rzeszow is effectively based on bus services only, consisting of two distinct sub-systems: the main city bus system (*MPK Rzeszow*) and the agglomeration bus system (*MKS Rzeszow*). The former is the core bus network of 58 lines, including the busiest lines with peak-hour frequencies of 10 minutes. Certain MPK lines also reach beyond the city administrative area. The latter (*MKS*) is a complementary system of 16 bus lines, serving outer areas and connecting them with the city center.

Historically, the rail system in Rzeszow has not played a significant role in regional or commuting trips. This is only changing now with the gradual development of the Rzeszow Suburban Rail system (PKA – *Podkarpacka Kolej Aglomeracyjna*) [21]. The PKA system provides regular train services along each rail corridor in and out of Rzeszow (eventually, every 30 minutes at peak hours), as well as new train stops throughout the city (currently under construction).

Both the MPK and MKS networks envisage variable service frequencies. During peak hours, it may take between 10 and 40 minutes for main within-city and suburban services. Feeder services (especially in outer areas) operate at lower frequencies, with certain services being ceased outside of peak hours or on weekdays. The bus network design in Rzeszow tends to favor direct connectivity over high service frequencies, and transfers are not popular. Thus, certain bus operations can be insufficiently effective in terms of passenger loads. Coupled with the rising popularity of private cars, this may induce the well-known vicious cycle of PT ineffectiveness [9] and has already led to PT service cuts in recent years.

### 2.2. Future PT scenarios – assumptions

Various proposals for a new rail-based PT system in Rzeszow are being coined in strategic discussions [20, 22 – 23]. These revolve around two essential concepts. The first would foresee a new tram (LRT-based) network, linking the city center with the main (and rapidly expanding) housing and industrial areas. The tram system was deemed a suitable, conventional mode of transport for a constantly growing mid-sized city. A second, less conventional proposal, which has emerged in the past decade, would involve a new monorail (HRT-like) system running overground along main travel routes in Rzeszow. The monorail project has inspired a heated public debate. On the one hand, it was perceived as an innovative solution; on the other hand, its eventual cost-benefit effectiveness would be a major unknown (and a valid risk), as such systems are very uncommon in European cities.

Tram and monorail system ideas in Rzeszow were often short-lived and limited to the conceptual stage. Passenger flow forecasts and/or appraisal studies were missing in the majority of such debates. Limited research evidence [22] suggests a more prospective role for the tram system in PT journeys than that of the monorail system. This study did not consider other policy measures that could further influence the relative attractiveness of public vs. road transport in Rzeszow. Nonetheless, the potential for developing a new urban rail mode in Rzeszow has already been indicated in previous studies [22–23]. A new urban rail solution could enhance the accessibility of expanding urban developments and reverse the dominant role of private cars in everyday journeys.

Table 1

Scenario assumptions – PT development proposals in Rzeszow

| **Scenario code** | ***Core* PT mode** | **Basic characteristics – urban PT network** | | | | | **Additional measures in transport network** |
|---|---|---|---|---|---|---|---|
| | | Network length [km] | | Max. peak frequency [mins] | Avg. travel speed [km/h] | Avg. stop spacing [m] | |
| **[W0]** | **Bus**<br>(ref. scenario) | Bus: | 244.1 | 10 | **25.6** | **550** | (none) |
| **[W1]** | **Monorail**<br>(HRT) | HRT:<br>Bus: | 21.5<br>225.5 | | **31.0**<br>26.1 | **930**<br>540 | |
| **[W2]** | **Tram**<br>(LRT) | LRT:<br>Bus: | 34.9<br>235.6 | | **24.2**<br>26.4 | **520**<br>540 | |
| **[W3]** | **Monorail**<br>(HRT) + | HRT:<br>Bus: | 21.5<br>225.5 | | **31.0**<br>26.1 | **930**<br>530 | **+ road capacity reduction in city centre** |
| **[W4]** | **Tram**<br>(LRT) + | LRT:<br>Bus: | 34.9<br>235.6 | | **24.2**<br>26.4 | **520**<br>540 | |

In the subsequent analysis, we formulated two scenarios for new urban PT system development in Rzeszow (Table 1, Figure 1). Each scenario assumed that a new rail-based PT mode (LRT or HRT) formed the main (core) part of the city's transport system, serving the main travel routes within Rzeszow.

Also, both scenarios reflect two distinct PT network design approaches concerning network layout, stops' spacing (and, hence, system accessibility) and operating speeds:

- **[W1] – the HRT scenario**. A new heavy rail system, akin to **monorail** transit, was introduced in Rzeszow. It features a corridor-based network model, with four HRT lines running along main radial transport corridors in Rzeszow and intersecting at the central-city PT interchange (next to the main railway station). The HRT system is designed with operating speeds of 31 km/h, peak-hour frequencies of 10 minutes, and stop spacing between 700 and 1000 m.
- **[W2] – the LRT scenario**. A conventional **tram** network was launched across the wider city area, resembling a grid-based network model. Its routes are served by 12 tram lines, operating at peak frequencies of every 10 minutes. Compared to the monorail network, the tram system features lower operating speeds of (on average) 24 km/h but a denser stop spacing of 350–700 m. We assumed it was developed as an on-street tram system, with tracks separated from road traffic wherever possible and with network-wide signal priority at intersections.

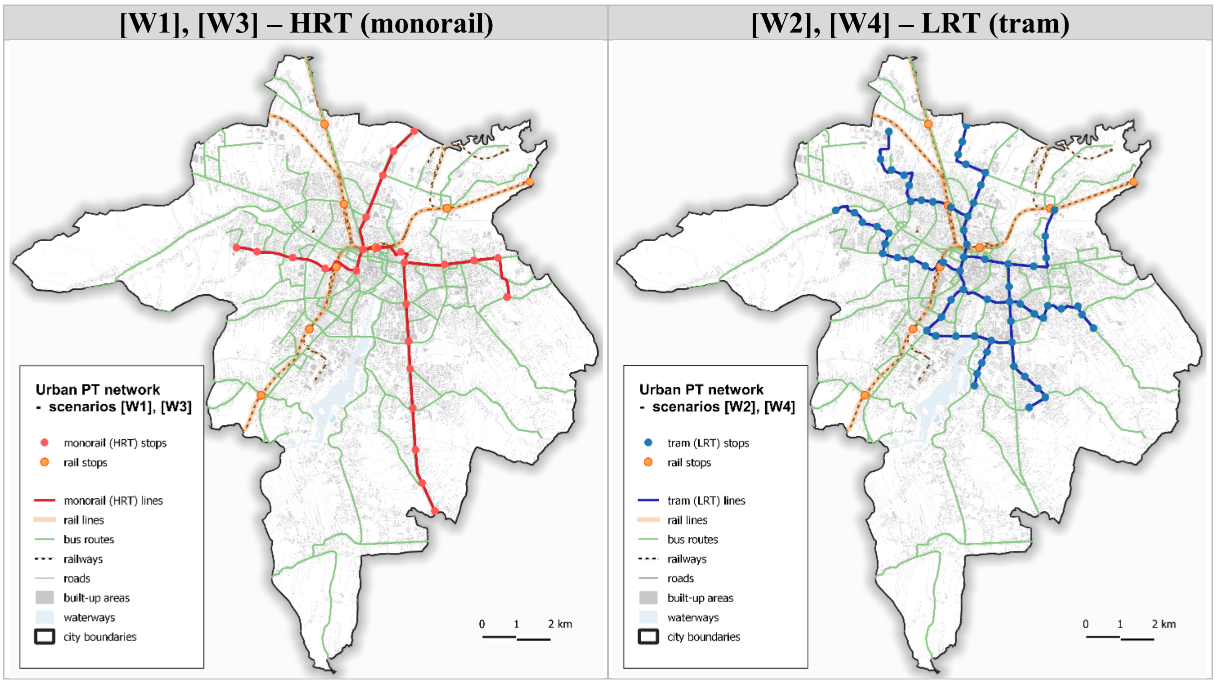


Fig. 1. Proposed HRT (left) and LRT (right) systems in the urban PT network of Rzeszow

Hence, both the [W1] and [W2] proposals feature different core PT network designs, with trade-offs between higher operating speeds (HRT) and greater network accessibility (LRT). Additionally, the existing bus network was redesigned to avoid duplicating the service capacity between parallel bus and LRT/HRT routes. Where appropriate, bus services were reduced to complementary (feeder) role, leading to 15% fewer service-km, or equivalently vehicle-km, in the [W1] and even 28% in the [W2] scenario when compared to the [W0] network. Taking into account all the PT transport modes in Rzeszow city, network (supply) optimization results in total service-km reductions of 12% in the [W1] scenario and 20% in the [W2] scenario (during peak hours). Additionally, to minimize the potential travel disutility due to regulatory barriers, we assumed an integrated fare policy across all PT modes in all scenarios.

The total length of the HRT network in [W1] is ca. 21.5 km, compared to 34.9 km for the whole tram network in [W2]. Although relatively shorter than the tram solution, the HRT project is likely to be more cost-intensive [3, 17], both during the investment and operational stages.

Moreover, in our simulation analysis, we introduced two scenarios with additional mobility measures, comprising road capacity reduction and influencing travel behavior in Rzeszow (Fig. 2). The same set of measures is assumed for the HRT and LRT proposals, yielding [W3] and [W4] scenarios, respectively. The objective was to investigate whether extra non-PT measures may synergically foster the benefits of monorail/tram proposals. These measures comprised:

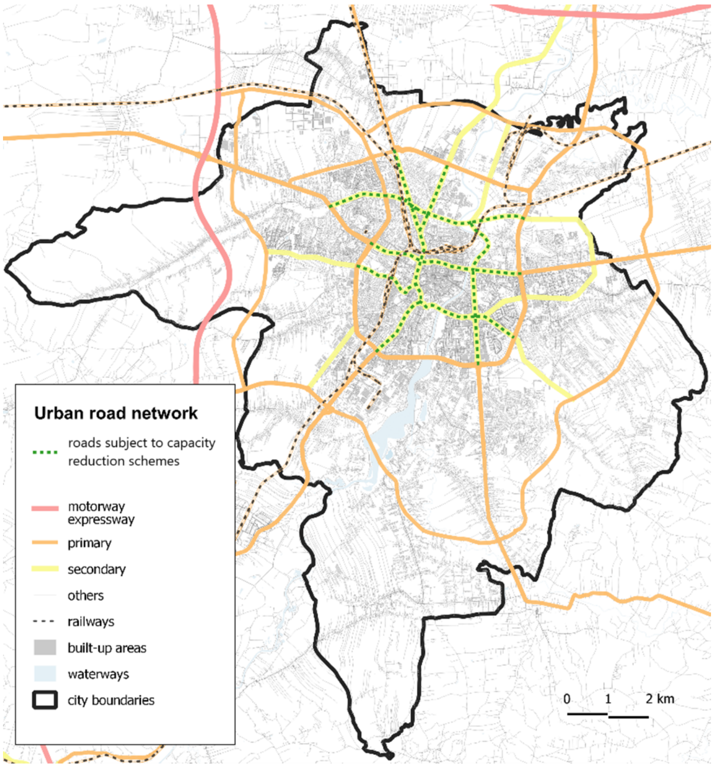


Fig. 2. Urban road network in Rzeszow with the proposed capacity reduction scheme in the [W3, W4] scenarios

- **Road capacity reduction within the city ring road**. On the supply side, one traffic lane per direction along the dual-carriageway roads was converted for PT, taxis, ride-hailing services, authorized use (e.g., police), and high-occupancy vehicles (with a minimum of two passengers) only. Alternatively, in the [W2] and [W4] scenarios, these traffic lanes could also be redesignated as tramway tracks. This implies that one or two traffic lanes per direction are left for general traffic use during peak hours (additional lanes may be available on intersection approaches, such as for turning movements.) Lowered road capacity in the city center aims to reduce traffic externalities (congestion, emissions, safety) and shift the car traffic outwards onto the (dual-carriageway) ring road, which effectively becomes the backbone of the city road traffic system.
- **Mobility behavior shifts**. On the demand side, the aim was to model the prospective changes in the perceived attractiveness of sustainable transport modes. Such changes may occur in the long term in response to transport policy measures, adjustments in one's own travel routine, campaign and promotion strategies, new ICT solutions, and improved comfort and travel time productivity of PT journeys [24–25]. Demand-side changes involved essential changes in modal choices arising from increased parking costs within the city center, a 10% greater perceived utility of walking, cycling, and PT journeys, and a 10% lower perceived utility of car journeys. While these are fixed assumptions, they can serve as proxy measures resembling the potential of favorable changes in passengers' travel behavior that may occur in the future.

## 3. METHOD

This section describes the research methodology of this study. The potential effects of PT development proposals in Rzeszow are assessed using GIS-based accessibility analysis and four-step transport demand modeling.

### 3.1. Transport modeling

The multi-modal transport model of Rzeszow was used to forecast the ramifications of proposed network scenarios. It is a classical macroscopic transport model developed in the PTV VISUM modeling software [26]. It consists of supply and demand sub-models, which represent transport system components and their interactions within the city limits. The Rzeszow transport model, developed based on 2016 travel surveys [27] and subsequently updated, was acquired for these research purposes.

**The transport supply sub-model was constructed as an oriented mathematical graph consisting** of nodes and arcs. This graph represents the road and PT network in the city of Rzeszow, comprising junctions or PT stops (nodes) connected by road links or PT lines (arcs), respectively. Each network element was parameterized with relevant attributes, including allowable transport systems (road traffic, bus, tram, rail, walk), free-flow speed, capacity (in vehicles per hour), and volume-delay functions. The PT network model was described with line routes and stop points, dwell times (at stops) and run times (between stops), as well as departure timetables.

**The transport demand sub-model was developed according to the classical four-step specification,** as specified in both scientific literature and practical guidelines [28]. Transport demand was calculated at the level of individual transport area zones (TAZs). In total, the city area was subdivided into 120 internal TAZs, plus 25 external TAZs representing main road and rail inlets/outlets at the city boundaries. The four-step demand model comprised a set of mathematical formulas that describe travel demand (activity) patterns within the city. These comprised the consecutive stages of trip generation, trip distribution, modal choice, and trip assignment. The demand sub-model formulas were based on city travel surveys and are described in full detail in the model specification [27].

The ultimate result of transport modeling was the assignment of demand onto the supply network, yielding road traffic and PT passenger flows (volumes) for a specific scenario. Further outputs are derivable from a wide range of parameters, both for individual network components (e.g., node/arc flows, link travel times, volume-capacity ratio) and globally (e.g., modal split, mean travel times and speeds, aggregate network loads). In this study, simulations in the Rzeszow transport model and resultant parameters were evaluated for the PM peak-hour period.

### 3.2. Accessibility analysis

The PT accessibility can be evaluated using various approaches, including empirical surveys (e.g., perceived accessibility scale) or network analyses (e.g., assessment based on GIS or GTFS (General Transit Feed Specification)) [29]. The latter approach was used in our study, as it allowed us to assess numerically the accessibility of a new urban PT network in the context of population density and land-use development within a specified catchment area. To this end, we utilized the open-source Quantum GIS software [30], in which the GIS analytical model for the Rzeszow city area was set up, consisting of supply and demand layers. The supply layer represents the urban PT network graph – stops, stations, and line segments– directly imported from the transport model. Input data for the demand layer is imported from the National Database of Topographic Objects [31], which contains information on built-up development within the city area. Based on this data source, the spatial distribution of the city population was calculated utilizing additional information from the 2021 National Census (*NSP 2021*) [19]. Thus, the output GIS demand layer represents the (estimated) population distribution in all the TAZs across the Rzeszow area at the level of individual buildings (i.e., address points), updated with prospective land-use projections.

The developed GIS model was then used to calculate population rates within the specific access range to and from the urban PT system. These walking isochrones were based on actual network topology and account for spatial barriers that may impair accessibility, such as rivers and rail embankments. In further analysis, two accessibility thresholds were examined, corresponding to a five- or 10-minute walking distance to/from the nearest stop (or station) of the newly proposed monorail/tram system, plus (additionally) the existing rail system. Isochrones of five to 10 minutes are commonly assumed as acceptable access range to/from the PT stops [32]. These reflect whether the given PT network structure is conveniently accessible to prospective users by walking, while more distant areas can be deemed as unserved by or excluded from the PT services.

## 4. RESULTS

This section presents the analytical results of this study. The main implications of the proposed PT development scenarios in Rzeszow are outlined and compared below. These are illustrated with numerical and graphical outputs of modeling analyses.

### 4.1. Transport modeling

| [W0] – road network flows | [W0] – PT network flows |
|---|---|

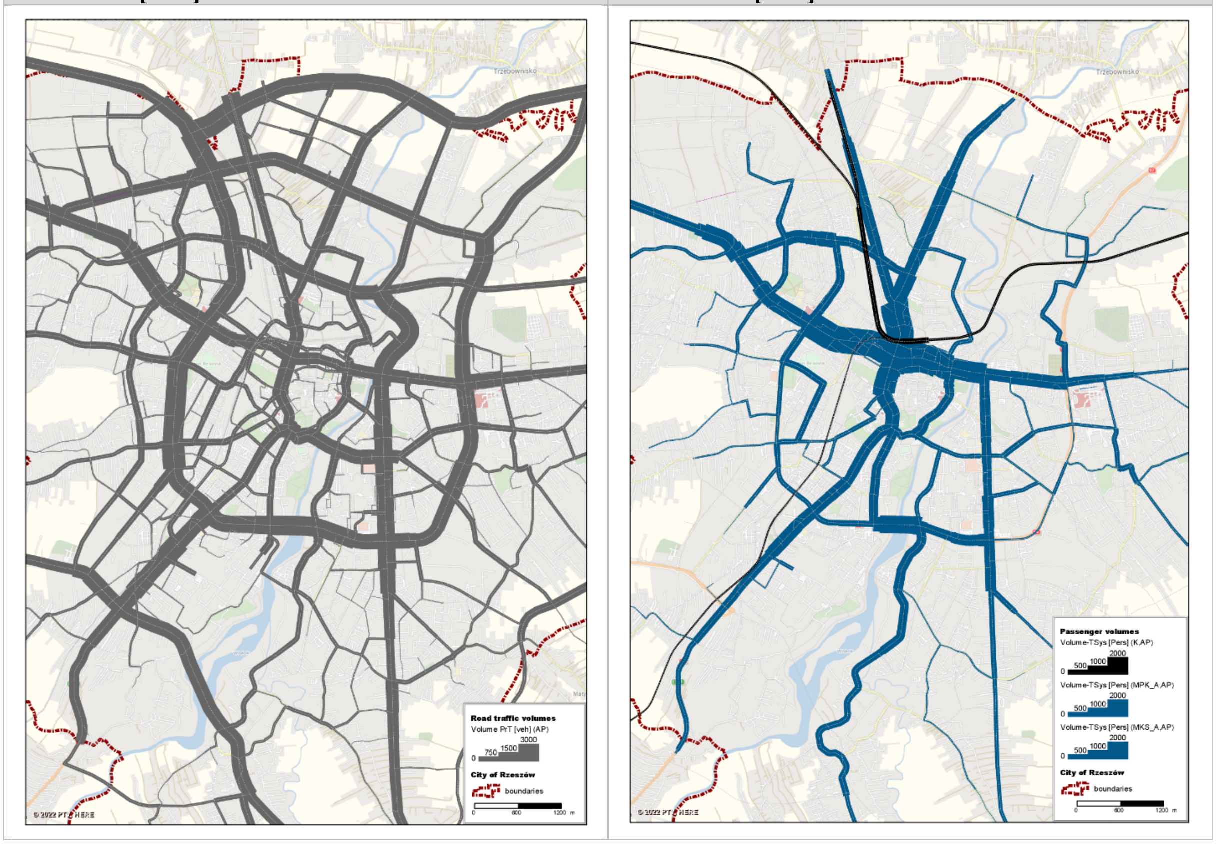

Fig. 3. Peak-hour travel flows in the urban road (left) and PT (right) transport networks of Rzeszow city, projected in the baseline [W0] scenario

Fig. 3 presents the baseline trip flows in the Rzeszow transport network (i.e., projected for the [W0] scenario). In general, road traffic volumes were distributed across multiple road network elements. Substantial traffic loads were observable along the city ring road, in suburban areas (i.e., main arterials), and notably, in the city center (i.e., along main W-E and N-S routes). Traffic volumes may peak around 3,000-4,000 veh./hr at the most loaded road cross-sections, also in close vicinity of the city center. Meanwhile, traffic volumes are lower (at ca. 1,500-2,500 veh./hr) along certain road sections in central Rzeszow, where one of two traffic lanes was open to PT and taxi services only during peak hours. Regarding the PT network, passenger flows exhibited a more concentric pattern, rising gradually towards the central Rzeszow area. Although bus routes in suburban areas are used rather sparsely, passenger volumes increase substantially along main routes inside the ring road. Peak volumes were projected to be around 4,000-5,000 passengers per hour (in cross-section) along the central W-E and N-

S bus corridors. As expected, the bus was the dominant PT mode. The present-day rail system does not play a significant role within the city or to/from the agglomeration area. Additionally, the [W0] results highlight the significant role of private cars, which are used in over 60% of everyday motorized trips.

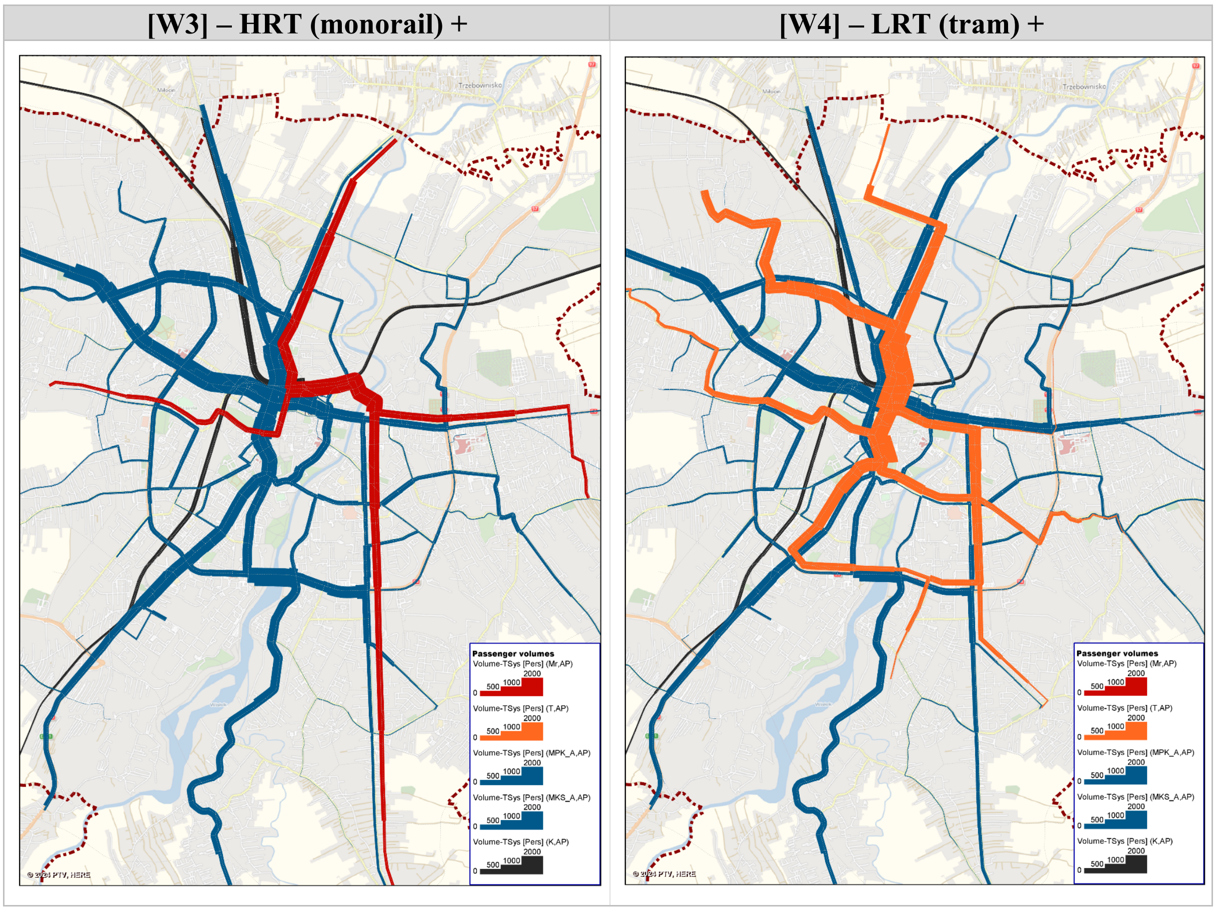


Fig. 4. Peak-hour passenger flows in the PT network of Rzeszow, with new LRT (left) tram (right) systems projected in the [W3] and [W4] scenarios, respectively

The development of a new urban PT system visibly influences network performance and projected travel flows in Rzeszow, as shown below in Fig. 4 and Tables 2–3. The new HRT and LRT systems proposed in the [W1] and [W2] scenarios, respectively, attract passenger flows from the existing bus corridors. The HRT network witnesses the cumulation of passenger flows towards the city center, with cross-sectional volumes peaking at 3,000 passengers per hour along the central HRT section (Fig. 4, left). The monorail radial routes carry approx. 1,000–2,500 passengers per hour inside the ring road. Passenger volumes then gradually diminish as they approach the city outskirts. In the monorail scenario, it is evident that the bus network remained a crucial PT transport mode along other travel routes outside of the HRT service range. Bus passenger volumes in the [W1] scenario peaked at around 4,000 passengers per hour along critical bus corridors within the city area.

Meanwhile, the LRT network in the [W2] scenario appeared to play a relatively significant role in the PT system of Rzeszow. Passenger flow forecasts (Fig. 4, right) indicate high passenger loads in the central city, reaching up to 4,000 passengers per hour along the core N-S tram corridor. Tram loads oscillated around 1,000-3,500 passengers per hour inside the ring road and up to 2,500 passengers per hour along tram connections towards main residential areas (northwest and southeast of the city center). Bus loads could also reach substantial passenger numbers, though this effect is less pronounced than in the [W1] scenario.

It is important to note that for both presented HRT and LRT concepts, urban rail and bus routes overlap along some of the network corridors. This may result in mutual competitiveness and split relatively high passenger flows between two distinct PT modes, lowering their operational efficiency. This issue can be addressed by either further extending the HRT or LRT network (to increase their catchment area and achieve global scale-up benefits) or optimizing the combined urban rail and bus design towards a trunk-and-feeder system, which is an interesting topic for follow-up studies.

Table 2

Transport modeling outputs – changes in road traffic network parameters

| Analysis scenario | | | Road traffic network parameters | | | | |
|---|---|---|---|---|---|---|---|
| | | | Total trips (within-city) [veh./hr] | Modal share [%] | Mean travel time [mins] | Network load changes [veh.-km] | |
| | | | | | | City of Rzeszow | Inside the ring road |
| **[W0]** | **Current state** | | 33 390 | 71.2% | 13.8 | n/a | n/a |
| *Changes relative to the [W0] scenario* | | | | | | | |
| **[W1]** | **HRT (monorail)** | | 33 000 | - 0.7 p.p. | - 0.1 | - 0.6% | - 0.6% |
| **[W2]** | **LRT (tram)** | | 32 910 | - 0.9 p.p. | - 0.1 | - 0.7 % | - 0.9% |
| **[W3]** | **HRT +** | **Road capacity reduction** | 30 520 | - 5.4 p.p. | + 1.2 | - 2.5% | - 18.8% |
| **[W4]** | **LRT +** | | 30 360 | - 5.8 p.p. | + 1.2 | - 2.7% | - 19.1% |

Table 2 outlines changes in road system performance within the city in the simulated peak hour. Both the [W1] and [W2] scenarios resulted in limited impacts upon private (car) transport in Rzeszow, with the [W2] tram scenario being slightly more advantageous. Compared to the base [W0] scenario, the modal shift to PT did not exceed one percentage point. Road network loads, measured by total veh-km traveled, remained roughly the same as in the [W0] scenario, decreasing by less than 1%. Significant changes are only observable in the [W3] and [W4] scenarios (i.e., assuming additional central-city road capacity reduction and mobility changes). The [W3] and [W4] scenarios exhibited substantial modal shifts of 5.4 and 5.7 percentage points, respectively, implying a 10% decrease in car usage within Rzeszow city. This is further reflected in the reduction of road network loads by almost 20% within the ring road perimeter. On a city-wide scale, road network loads dropped by ca. 3%. Interestingly, such changes were not accompanied by major deteriorations in car journey parameters, as average travel time rose by 1.2 minutes per trip. Likewise, the [W4] tram-based scenario reductions in traffic externalities are somewhat greater than in the [W3] monorail-based scenario.

Table 3

Transport modeling outputs – changes in urban PT network parameters

| Analysis scenario | PT network parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total trips (within-city) [pass. per hour] | Modal share [%] | Mean travel time [mins] | Performance indicators - *rel. change vs. [W0]* | | PT sub-modes' ridership | | | |
| | | | | Transfers | **Avg. load indicator** | Bus | Rail | **HRT (m'rail)** | **LRT (tram)** |
| **[W0]** | 16 210 | 28.8% | 18.9 | *n/a* | | 94.5% | 5.5% | *n/a* | *n/a* |
| **[W1]** | 16 600 | 29.5% | 17.6 | + 7.8% | **+ 7.4%** | 73.8% | 8.4% | **17.9%** | *n/a* |
| **[W2]** | 16 690 | 29.7% | 17.3 | + 8.7% | **+ 10.2%** | 62.9% | 6.7% | *n/a* | **30.4%** |
| **[W3]** | 19 080 | 34.3% | 17.3 | + 6.8% | **+ 8.3%** | 74.5% | 7.8% | **17.7%** | *n/a* |
| **[W4]** | 19 240 | 34.6% | 17.0 | + 7.7% | **+ 12.1%** | 62.6% | 6.2% | *n/a* | **31.2%** |

Table 3 illustrates shifts in PT system performance in Rzeszow in our analytical scenarios. Both the introduction of the HRT system in the [W1] scenario and the LRT network in the [W2] scenario led to slight increases in the PT modal share, from approx. 29% to 34-35%. Mean travel time was reduced from 18.9 minutes per trip in the base [W0] scenario to 17.6 minutes for the HRT system and 17.3 minutes for the LRT system. The tram network also plays a much greater role in the PT system of Rzeszow, carrying approximately 30% of all passenger flows, compared to 18% in the case of the monorail network. These patterns are further fostered in the [W3] and [W4] scenarios, which envision road capacity reduction in central Rzeszow and changes in mobility behavior. The [W3] and [W4] outputs indicate substantial growth in PT modal share, which eventually reached ca. 35% on a city-wide scale. Benefits were again more pronounced for the [W4] tram scheme, with a mean travel time of 17.0 minutes per trip.

A final and aggregate performance indicator of the proposed PT systems is the *average PT loading indicator*. It was evaluated as the ratio of the total number of passenger-kilometers versus total service-kilometers during the (simulated) peak hour in Rzeszow. Higher PT ridership indicator values are indicative of greater operating efficiency in the PT network, as more PT demand (passenger flows) was served by the same amount of PT supply (vehicle trips). The resultant changes are shown in Table 3, indicating improvements across all investment scenarios. Compared to the baseline [W0] scenario, the average PT loading indicator grew by 7% in the [W1] HRT scenario and by 10% in the [W2] LRT scenario. The [W3] and [W4] mobility measures foster these favorable changes, yielding values of 8% and 12%, respectively. The highest PT network utilization efficiency rate is attainable in the [W4] scenario, which involves the simultaneous inclusion of road capacity reduction and changes in mobility behavior.

### 4.2. Accessibility analysis

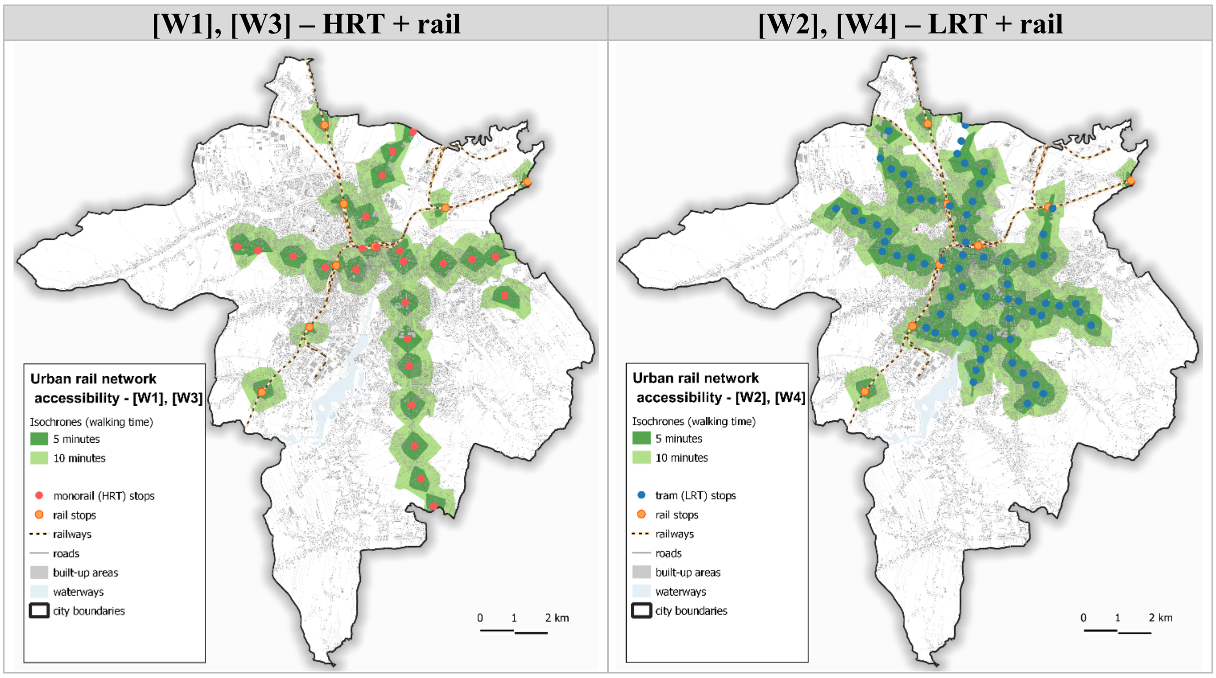


Fig. 5. Accessibility isochrones for the proposed LRT (left) and tram (right) networks, plus the existing rail network (both)

Fig. 5 depicts the catchment areas of the proposed urban PT systems. Accessibility isochrones were evaluated as five- and 10-minute walking distances from the PT stops (stations) of existing rail services, plus new tram (LRT) or monorail (HRT) services. These plots show that the grid-based tram network has greater overall spatial accessibility. Denser stop spacing implies that a greater share of the population and built-up areas are served more conveniently by the proposed tram network. Moreover, a vast majority of the central city area is reachable within a maximum of five- or 10-minute walk to/from the nearest tram stop. Accessibility analysis results for the monorail network are less favorable. The HRT improves the overall urban PT network coverage of built-up development in Rzeszow, especially within main travel corridors in/out of the city center. However, owing to its radial network structure, major population areas in Rzeszow are still unserved by the combined rail and HRT network and, notably, within the city ring road. In contrast to the LRT network, a greater share of trip origin/destination points are within walking distance to/from the HRT stations longer than five minutes.

The above observations are reaffirmed by numerical findings in Table 4. The Tram network is accessible within a five-minute walk for ca. 42% of the (projected) city population, whereas, for the monorail network, the corresponding rate is only 12%. Differences are less conspicuous when assuming a 10-minute accessibility criterion to the combined rail and HRT/LRT network but still more advantageous in the LRT scenario (almost 70%) than for the HRT scenario (ca. 45%). Overall, a five-minute isochrone to/from the tram network covers approx. a twice higher share of built-up development in Rzeszow (including housing, services, and industrial developments) than to/from the monorail network. In particular, housing and workplace locations are better served by the proposed tram system.

Table 4

Accessibility analysis output – estimated population within the range to/from the proposed urban rail network in Rzeszow

| **City population within the catchment area (access time) of urban rail stops:** | | **Network scenarios** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **[W1], [W3]** | | | | **[W2], [W4]** | | | |
| | | **HRT** (monorail) | | **HRT + rail** | | **LRT** (tram) | | **LRT + rail** | |
| | | 5 [mins] | 10 [mins] | **5 [mins]** | **10 [mins]** | 5 [mins] | 10 [mins] | **5 [mins]** | **10 [mins]** |
| **Housing type** [pop. est.] | Low-density | 6 210 | 20 420 | 6 860 | 24 040 | 14 370 | 29 820 | 14 980 | 32 700 |
| | High-density | 16 840 | 66 090 | 19 650 | 69 000 | 66 500 | 104 700 | 66 670 | 107 340 |
| **Population** [total] | | 23 050 | 86 510 | 26 510 | 93 040 | 80 870 | 134 520 | 81 650 | 140 040 |
| **Population share** [%] | | 11.9% | 44.6% | **13.7%** | **48.0%** | 41.7% | 69.4% | **42.1%** | **72.2%** |

## 5. CONCLUSIONS

This study investigated the potential effects of introducing a new urban rail transport system in a mid-sized city. We conducted a comparative analysis of a new backbone PT system in a sample case study of Rzeszow, Poland (200,000 inhabitants). Two proposed solutions concern either a corridor-based heavy-rail (HRT) network or a grid-based light-rail (LRT) network. To this end, we utilized transport demand and network accessibility models to forecast PT ridership flows, capacity utilization, and overall transport system performance.

The present findings show how the introduction of a new rail-based system can result in more efficient urban PT performance in a mid-sized city such as Rzeszow. According to simulation outputs, both HRT (monorail) and LRT (tram) schemes lead to shorter PT travel times and higher PT attractiveness relative to private car trips. The existing bus connections are adjusted to provide supplementary (feeder) service, enhancing overall PT network loads. Moreover, road capacity reduction schemes and long-term changes in mobility behavior reinforce urban PT ridership even further. Results are more favorable in the LRT case in terms of greater PT travel time improvements and higher utilization rate of PT capacity. The grid-based tram network features a wider catchment area, as approx. 70% of the city population is within a maximum of a 10-minute walk from the nearest stop, while the corresponding rate for corridor-based monorail network equals about 45%. The [W4] scenario, which combines a tram system with road capacity reduction and mobility measures, yielded the largest benefits across the considered scenarios: on average, PT travel times were shorter by ca. 2 minutes per trip (ca. 10% reduction), PT ridership increased by 20%, and PT capacity utilization improved by 12% compared to the baseline [W0] scenario. Road capacity reduction measures resulted in a 20% reduction in car traffic loads across the central Rzeszow area. Interestingly, no major deteriorations occurred in private car trips, whose travel times are, on average, ca. 1.2 minutes longer.

Our study demonstrates how the prospective potential of new urban rail modes in mid-sized cities can be underpinned by transport simulation and accessibility models. Case study findings contribute to the state-of-the-art observations on urban rail solutions in such cities. While both HRT and LRT proposals are shown to increase PT popularity, the LRT systems seem better positioned to play an effective role as the core mass transportation PT system in the mid-sized city. Moreover, road interventions synergically foster the effects of newly introduced urban rail transport, reducing traffic loads (and the associated congestion and pollution problems) while encouraging higher PT ridership. In the long run, such a combination of policy instruments can lead to a more attractive urban mobility system with shorter and more reliable travel times, higher PT accessibility and network throughput, and reduced environmental externalities. Hence, new urban rail projects in mid-sized cities, such as Rzeszow, can also bring benefits beyond the transportation domain, stimulating urban regeneration and new development opportunities while successfully supporting climate change adaptation in urban systems.

The methods and findings presented in this study can support the feasibility analysis of various passenger rail proposals and their synergy (complementarity) with other transportation policies. This is especially important in mid-sized cities, which require solid, in-depth projections of future travel demand to justify new major investments and achieve positive spillover effects in other urban realm domains.

Our study is not exempt from limitations and can be extended by follow-up work in several ways. Evaluations of new PT investment schemes should be supplemented, in particular, by comprehensive cost-benefit analyses, accounting for both the investment and long-term operating costs. Additionally, in the context of modern-day climate mitigation objectives, feasibility studies should consider the environmental impacts and achievable emission reductions from the transport sector, where new rail projects can play an instrumental role. The integration of different PT modes can play a pivotal role in their eventual and synergistic effectiveness and could be the subject of further research scrutiny in the context of integrating physical infrastructure (e.g., seamless transfers), tariff policy (e.g., uniform fare system), etc. From a local perspective, more detailed studies should establish an optimum LRT (or HRT) network layout to solve the classical transit network design problem to maximize its operational efficiency and minimize the potential overlap of PT bus and rail lines. Our study focused on tram and monorail modes, which dominate the case study city transport debate; their potential could be compared with that of other rail-based schemes or BRT systems. Finally, future transport modeling studies need to account for valid aspects in urban PT networks, such as the effects of capacity constraints, network robustness and vulnerability, demand elasticity, PT priority measures, and the potential of emerging ITS solutions.

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