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Article

Will new tram lines enhance the connectivity and walkability? A case study of Sakarya

Yavuz Halimergün[1], Abdulkadir Özden[2], Süleyman Nurullah Adahi Şahin[2,*], Hakan Kocaman[1]

[1] Graduate Education Institute, Sakarya University of Applied Sciences, 54050 Sakarya, Turkey
[2] Civil Engineering Department, Sakarya University of Applied Sciences, 54050 Sakarya, Turkey
*** Corresponding author:** Suleyman Nurullah Adahi Şahin, adahisahin@subu.edu.tr

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Abstract: This study investigates the impact of planned tram lines on walkability and accessibility in Sakarya, utilizing Geographic Information Systems (GIS) for spatial analysis. The research evaluates the catchment areas of proposed tram stops, assessing their suitability and coverage, and examines how these areas integrate with existing public transport routes. By calculating time-oriented catchments for 5, 8, and 10-minute walking distances, the study identifies service gaps and redundancies in the public transport network. The findings reveal that the new tram lines will enhance accessibility by extending coverage to high-density areas and potentially reducing the demand on existing bus services. The analysis also highlights the overlap between bus transit lines and tram stops, suggesting optimizations to improve network efficiency. The results offer valuable insights for urban planners, aiming to optimize Sakarya's public transport system to be more inclusive and sustainable. This study contributes to urban mobility planning by providing a detailed understanding of how new tram lines can improve connectivity and support sustainable urban development.

Keywords: sustainable urban mobility; public transport; walking distance; station catchment area; accessibility

1. Introduction

Sustainable urban mobility is essential for the overall quality of life in cities. By adopting sustainable transportation practices, cities can achieve economic growth, environmental protection, and social diversity while ensuring efficient and comprehensive public transportation systems. The European Commission outlines that sustainable urban mobility plans aim to develop urban transport systems by addressing key objectives such as providing transport options for all citizens, improving safety, reducing pollution, enhancing efficiency, and contributing to the urban environment's quality [1]. Every facet of city life—including recreation, education, business, and industry—is linked with transportation. Indicators of sustainable urban mobility are vital for sound spatial planning, effective traffic management, and environmental protection [2].

Public transport plays a crucial role in achieving sustainable mobility in cities, necessitating the maintenance of supply and quality at acceptable levels [3]. Several research works highlight its significance for sustainable urban development, influencing not only transportation but also social cohesion, environmental sustainability, and energy efficiency [4–6]. Promoting walking, cycling, and a well-designed public transport system is pivotal for sustainable urban mobility [4,7]. Accessible public transport enhances mass mobility, improves urban life quality, and reduces environmental impacts [8,9]. It is also essential for developing inclusive urban environments, especially those that support social fairness and the elderly [10,11].

The primary function of a transportation system is to facilitate the movement of individuals from their current locations to their desired destinations within a reasonable timeframe, using appropriate infrastructure and means [12]. Creating public transportation systems with pedestrian-accessible stops that are within a comfortable walking distance can boost urban mobility, specifically on the local scale [13]. The ease with which people can reach public transport stops is a key determinant of accessibility [14,15].

The idea of transport system availability has been described using a variety of terminology, including “access,” “accessibility,” “availability,” and “proximity” [16,17]. Conceptually, accessibility can be viewed as either an activity (opportunities that are being taken) or a potential (opportunities that could be taken) [18]. Even those not currently using a particular form of public transport may consider it a future option, known as the value of the option. Accessibility signifies the general ability of people to have services and activities within their reach [19], translating to the time and money spent by individuals and companies on transportation. Corazza and Favaretto [20] link accessibility with terms such as “within walking distance” or “walkable.” The quality of access significantly impacts the quality of life both directly and indirectly. Several factors can affect accessibility, including the conditions of traveling by motor vehicle, the quality of transport modes such as walking, cycling, and public transit, the connectivity of the transport network, and the proximity of different types of land use (distances between activities) [21].

One measure of transit accessibility is its spatial coverage, or the transit service catchment area. Studies have shown that spatial accessibility to the public transport system is a fundamental factor in the use of transit; only with such accessibility will the user consider other elements such as cost, comfort, safety, etc. [22]. Poor access to public transport disproportionately impacts low-income individuals, the elderly, and women, potentially resulting in a lack of access to education, jobs, healthcare facilities, and hospitals [23–26].

A number of researchers have calculated the distance that locals are willing to walk to get to local destinations like schools and bus stops. The early research on this topic was published in 1976 regarding the numerical analysis of walking distance to bus stops [27]. Approximately 400 m has been shown to be a reasonable walking distance for people to walk in order to get to the closest transport station [28,29]. This willingness dramatically drops when the distance surpasses 580 m [30]. According to Loutzenheiser’s [31] research, the probability of someone walking to transit drops by 50% for every 500 m when they are farther from a station. Walking to the major modes, such as heavy and light rail systems, is found acceptable for 800 m [28] and 1600 m [32], where the latter is found less preferable.

On the other hand, there are many estimations regarding the walking speed of pedestrians. However, determining walking speed plays a vital role in traffic safety and urban planning processes. Walking speed may vary depending on not only age groups and physical disabilities but also seasonal conditions [33]. Arango Diaz [33] stated that the average walking speed of younger and older people is 5.80 km/h and 4.90 km/h, respectively. Walking speed of all pedestrian mean is 5.22 km/h [34]. Weather and climate conditions can affect the walking speed directly; for example, when walking on a snow-covered area, walking speed slows down by about 0.367 km/h compared to clean ground, whereas if the ground is not challenging, each temperature drop will increase walking speed [35].

The introduction of a light rail system can redistribute transit demand, potentially alleviating pressure on overloaded bus and paratransit lines [36]. Moreover, it can lead to shifts in urban mobility patterns, with a transition towards rail-based services and the gradual integration of rail into intermodal transportation networks [37,38]. Light rail systems can stimulate economic development and urban regeneration along their corridors, promoting higher density and mixed-use development, further enhancing accessibility. Research indicates that expanding public transportation systems, including light rail, can enhance access to healthcare services, particularly benefiting individuals with low incomes [39]. Furthermore, implementing transit-oriented development around rail-based public transportation can influence urban form, encourage redevelopment, and revitalize old areas [40]. On the other hand, a significant disadvantage of trams and other rail-based systems is their high initial infrastructure costs, making them less adaptable compared to bus-based transit systems, which can more easily adjust routes and expand networks [41]. Furthermore, trams operating in mixed traffic environments face challenges such as increased delays and safety risks, particularly in densely populated urban areas where interactions with road vehicles can affect their efficiency [42].

Evaluating the accessibility impacts of light rail involves assessing proximity to stops, service frequency, and connectivity with other transport modes. GIS-based analyses are particularly useful for visualizing and quantifying these impacts, allowing planners to identify service gaps and areas for improvement. Service area analysis helps understand the shifts in demand and mobility and plan accordingly [43]. In cities where there are only bus services, a possible light rail can act as the backbone of the transit network, with buses serving as feeder services to connect outlying areas to the light rail stops, ensuring seamless connectivity and efficient resource use [38,44]. By identifying overlapping service areas, planners can streamline transit services, eliminate redundancies, and enhance overall network efficiency [45].

Service area analysis in GIS for light rail catchment area determination involves advanced GIS techniques to define the spatial extent within which a transit station can attract passengers. A common method used is the service area approach, also known as isochrone mapping or ped shed analysis, implemented in GIS software like ESRI’s ArcGIS™ with the Network Analyst™ extension [46]. Methods for determining catchment areas include the proximity method using buffer rings and network-based service areas [47]. These methods delineate the coverage of service areas around transit facilities based on factors like Euclidean distance [48]. Radial-based catchment areas are also widely used in transportation planning to estimate the number of individuals within walking distance of a transit stop [49].

Researchers have explored algorithms to automatically generate station catchment areas, comparing methods like Euclidean distance transform algorithms and location-allocation methods [47]. These approaches efficiently define the reach of a transit station and understand interactions between supply and demand for public transit services [26]. Additionally, studies have focused on enhancing the accuracy of catchment area analysis by considering factors like street layout, land use, parking capacity, and multimodal accessibility [50]. Incorporating these variables into the analysis provides a more comprehensive understanding of the factors influencing the size and shape of catchment areas for light rail stations.

The aim of this study is to understand the impact of planned new tram lines on walkability and accessibility in Sakarya using Geographic Information Systems (GIS) for service area analysis. The study will calculate the catchment areas of proposed tram stops, examining their suitability and coverage. Additionally, it will assess the current tram line's catchment areas and evaluate parallel and overlapping public transport routes to understand their integration and overall efficiency. These analyses aim to shed light on optimizing the public transport network in Sakarya, contributing to the development of more inclusive and sustainable urban environments. This study was conducted in Sakarya, Türkiye, which is also shown on the maps in different scales (**Figure 1**). This project is planned by the Ministry of Transportation and Infrastructure and the General Directorate for Infrastructure and Investments in the Republic of Türkiye. Sakarya is a city located in the northwest of Türkiye. The population of Sakarya is 1,098,115 as of the end of 2023; the annual population growth rate is 16.6 per thousand; the surface area of the province is 4817 km^2, and there are 228 people per km^2 in the province. Sakarya ranks 22nd in Turkey in terms of population and 66th in terms of surface area [51].

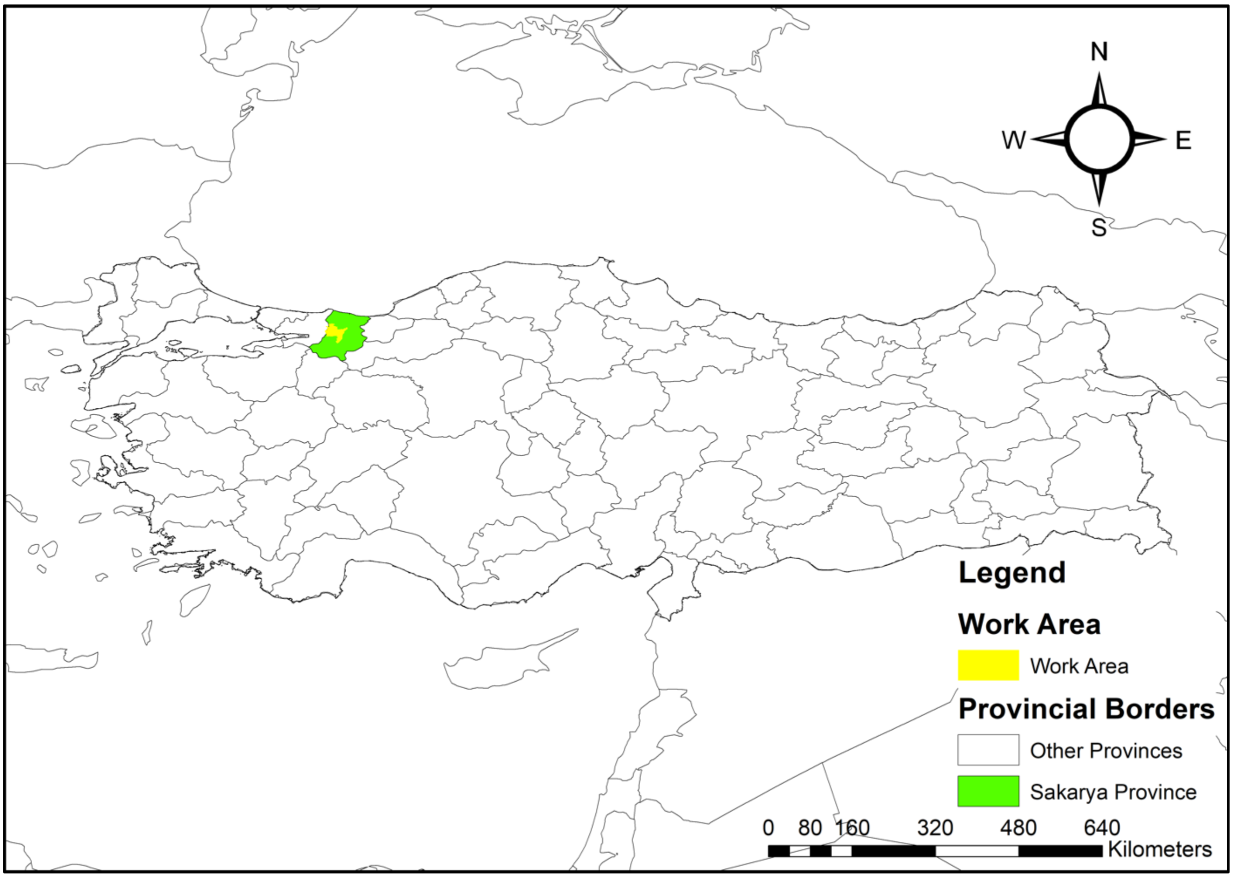

Figure 1. Location of the Sakarya where the analysis is conducted.

Both tram and bus lines are displayed on the same map to allow for effective monitoring (**Figure 2**). When the lines appear darker and thicker, it indicates that there are more concentrated bus lines in that area. The thickening of the red lines signifies an increase in the number of bus routes and stops. In areas where the tram line overlaps, the bus lines must be analyzed in terms of service frequency, the number of stops, and bus capacity. Another objective of the study is to assess passenger distribution and pooling behaviors once the tram line is implemented in the study area. This will provide a better understanding of the mobility and transfers between different modes of transportation, such as buses and trams.

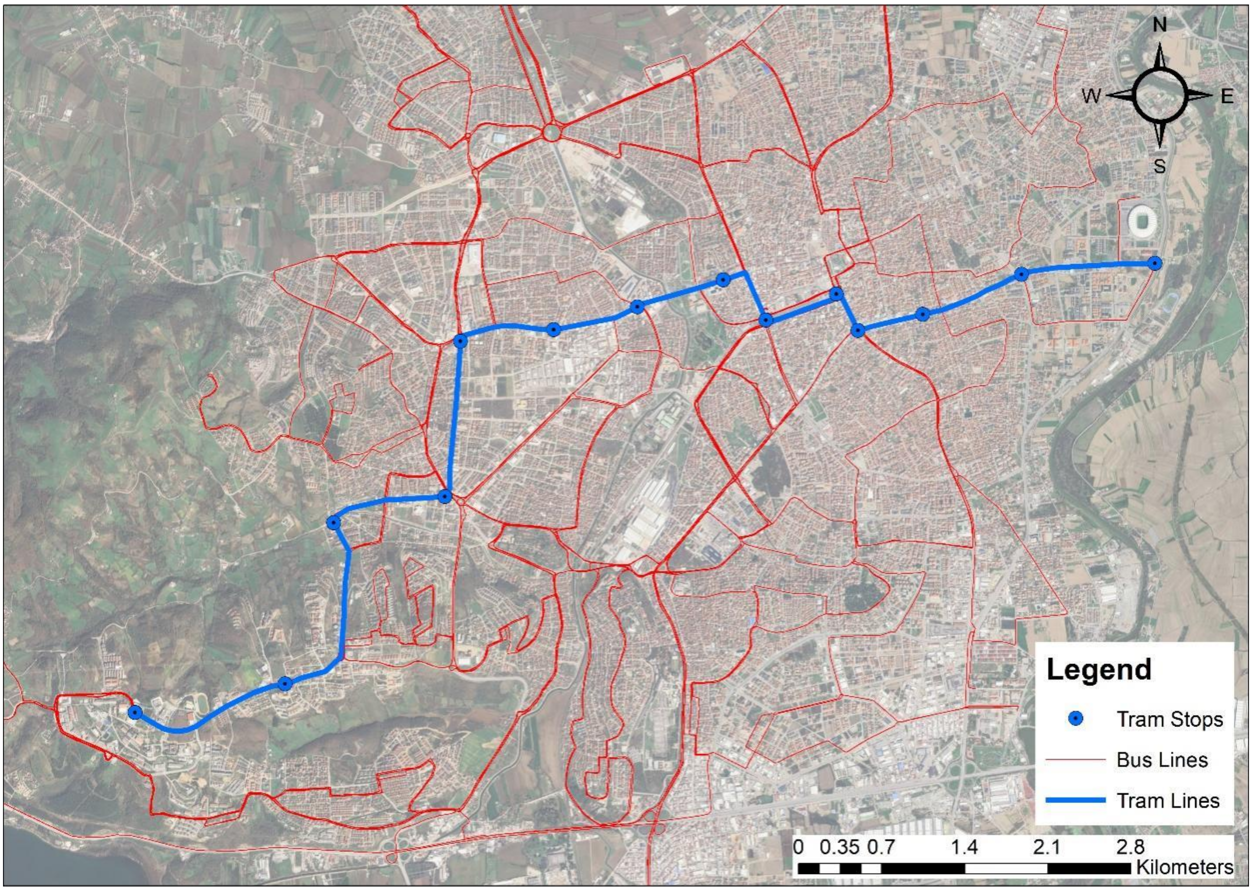

Figure 2. Both tram and bus lines are shown on the map with tram stops.

2. Materials and methods

To assess the catchment areas of a newly planned light rail line in Sakarya, this study employs ESRI's ArcGIS™ with the Network Analyst™ extension to conduct a detailed spatial analysis. Initially, the existing public transport infrastructure, including bus stops and routes, will be mapped to establish a comprehensive baseline. The proposed tram stop locations will be integrated into this map. Neighborhood boundaries and partial population data will also be incorporated to evaluate the demographic impacts, ensuring a thorough understanding of the service provided to various communities.

Service area analysis will generate time-oriented catchments delineating 5, 8, and 10-minute walking distances from each proposed tram stop. These maps will identify the spatial coverage and potential overlaps with existing bus routes, highlighting redundancies and service gaps. Integrating these datasets allows for a meticulous evaluation of parallel and overlapping routes, crucial for identifying inefficiencies where the new tram line may duplicate existing services. Based on the insights from this analysis, recommendations will be presented to optimize the public transport network, potentially including the removal or relocation of specific bus stops to enhance connectivity.

In this study, planned tram lines are investigated. The Sakarya Metropolitan Municipality prepared the implantation of tram lines in three phases in Sakarya, where Phase-1 was currently approved by the Ministry of Transport and Infrastructure. In this plan, Phase-1 covers the highly populated east-west coverage, including the university campus connection. On the other hand, Phase-2 and Phase-3 were planned to enhance the mobility infrastructure in the south-east of the city and intercity bus terminal connections. Phase-1 has a tram line length of 9 km, Phase-2 has a tram line length of 4.4 km, and Phase-3 has a tram line length of 9.26 km. However, the investigated tram line includes the entire Phase-1 and a part of Phase-3. There are 37 Bus Transit Lines that are analyzed in this study. There are 14 Tram Stops (Stations) to be investigated, and these stops are located in 7 different neighborhoods and 3 different districts. The outcomes will provide valuable insights for urban planners, facilitating the design of a more efficient and accessible public transport system in Sakarya. This methodical approach contributes significantly to creating a more inclusive and sustainable urban environment, aligning with broader urban development and mobility objectives.

3. Results

The tram line that is the subject of this study will be implemented in Sakarya, Türkiye. The tram system is planned to be built in three-phased like Phase-1, Phase-2 and Phase-3. Red line represents Phase-1 tram line which has 9 km and 11 Tram Stop, yellow-line refers to Phase-2 tram line, which has 4.4 km and 6 stations and the blue line presents Phase-3 tram line, which has 9.26 km and 12 stations. These line lengths and tram stations may change depending on the growth momentum of the city. In this analysis, walking speed was applied as 5 km/h. Considering a walking speed of 5 km/h, the walking distances for different durations are approximated as follows: a 5-minute walk covers approximately 416 m, an 8-minute walk spans about 666 m, and a 10-minute walk reaches roughly 832 m. The green, yellow, and red catchments will be structured according to these considerations.

Walking Time-Oriented Catchments are created based on 5, 8, and 10-minute walking distances. These areas were calculated on ArcGIS Service Area Analysis. However, when calculating these areas, the first condition was to calculate the appropriate walking paths for passenger use and then create a time-oriented catchment. It means that the coverage area (Walking Time-Oriented Catchment) is calculated by network analysis on the walkable lines. Walkable lines were detected as routes that people could walk clearly. The difference between Buffer Zone Analysis and Service Area Analysis is shown in **Figure 3** [52]. The total catchment area for each walking distance category is given in **Table 1**.

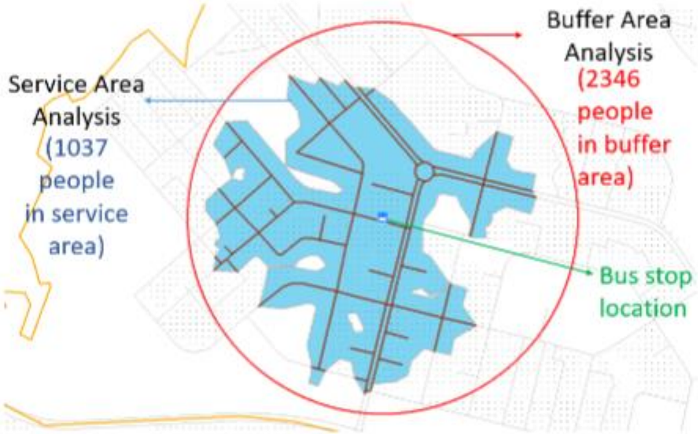

Figure 3. An example of the difference between service area analysis and buffer analysis coverage in GIS.

Table 1. Walking time-oriented catchments and areas with impacted bus stops.

Time (minutes)	Area (km^2)	Bus Stops	Bus Stops Density (Stop per km^2)
0-5	2.0405	72	35.3
0-8	6.0234	158	26.2
0-10	10.3992	236	22.7

Green, yellow, and red colored areas represent the distance between 0–5, 5–8, and 8–10 min, respectively (**Figure 4**). The area of the green zone, yellow zone, and red zone is 2.0405 km^2, 3.9829 km^2 and 4.3758 km^2 in total.

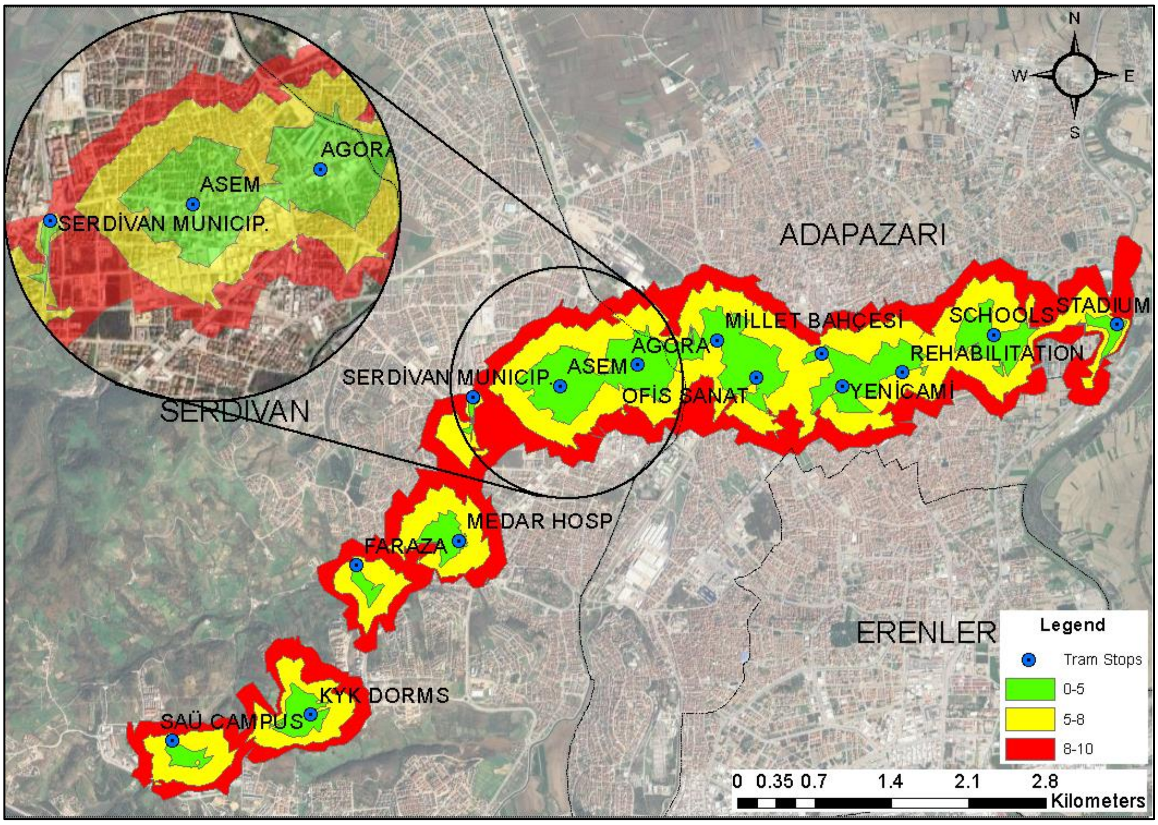

Figure 4. Walking time-oriented catchments with basemap.

Additionally, bus stops in the catchment area of the new tram line are presented in **Figure 5**. The same color coding is used for representing the bus stops in designated catchment areas. There are a total of 236 bus stops located near the tram line, where 72, 86, and 78 bus stops are in green, yellow, and red catchment areas, respectively. This result shows that there are 72 bus stops within a 5-minute walk of the tram stop, 158 (72 + 86) within an 8-minute walk, and 236 (72 + 86 + 78) within a 10-minute walk.

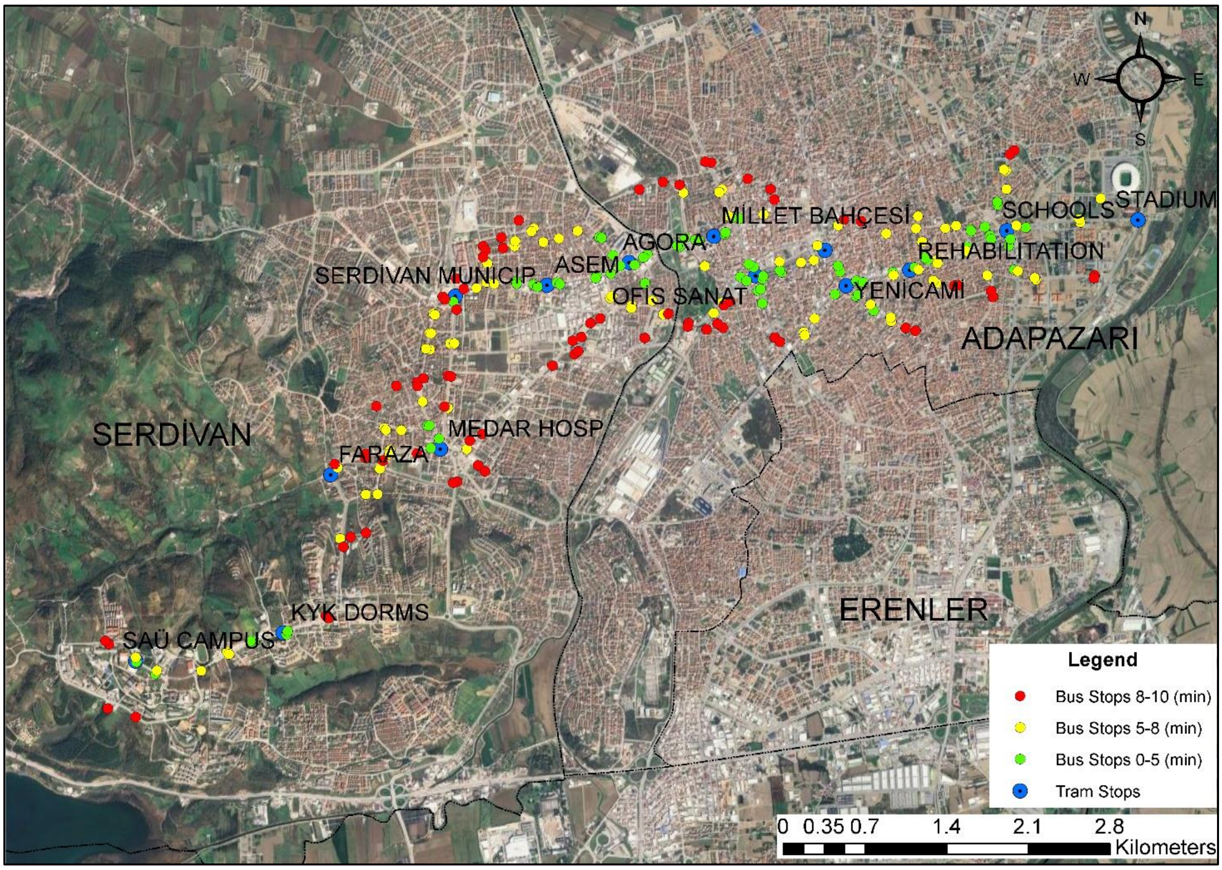

Figure 5. Tram stops (big blue-colored shape) and bus stops (green, yellow, and red-colored dots) are shown on the same map. (There are 72 stops (5-minute walking catchments green-colored dots on the map), 86 stops (between 5 and 8-minute walking catchments yellow-colored dots on the map), and 78 red bus stops (between 8 and 10-minute walking catchments red-colored dots on the map).

Considering the purpose of the light-rail and the necessity of re-evaluating the existing public transportation systems in the area helps enhance the effectiveness of the network by reducing redundancies and planning the mode-share. Thus, the 236 bus stops with parallel bus lines should be carefully evaluated. The 72 bus stops that are 5 min walking distance from the tram stations (green region) could be removed except the ones that will be used as a transfer point for a mode chance (switching from bus to tram or vise verse). Additionally, the remaining 164 bus stops in 5–10 min walking distance (yellow and red regions) should be evaluated based on the possible changes in bus routes.

Moreover, population density is used to better understand the extend of the coverage where the new tram line is planned. It is calculated by dividing the population of a neighborhood by the area of the neighborhood. Population density map was achieved through interpolation of neighborhood-oriented population data, which is published by the Turkish Statistical Institute, TÜİK [53], allowing for estimation of point population density (**Table 2**). A population density map is created by ESRI's ArcGIS™ based on the neighborhood's population data (**Figure 6**). According to these maps, population densities as a point information of tram stops were generated. Thus, estimated population density was shown for each tram stop (**Table 2**).

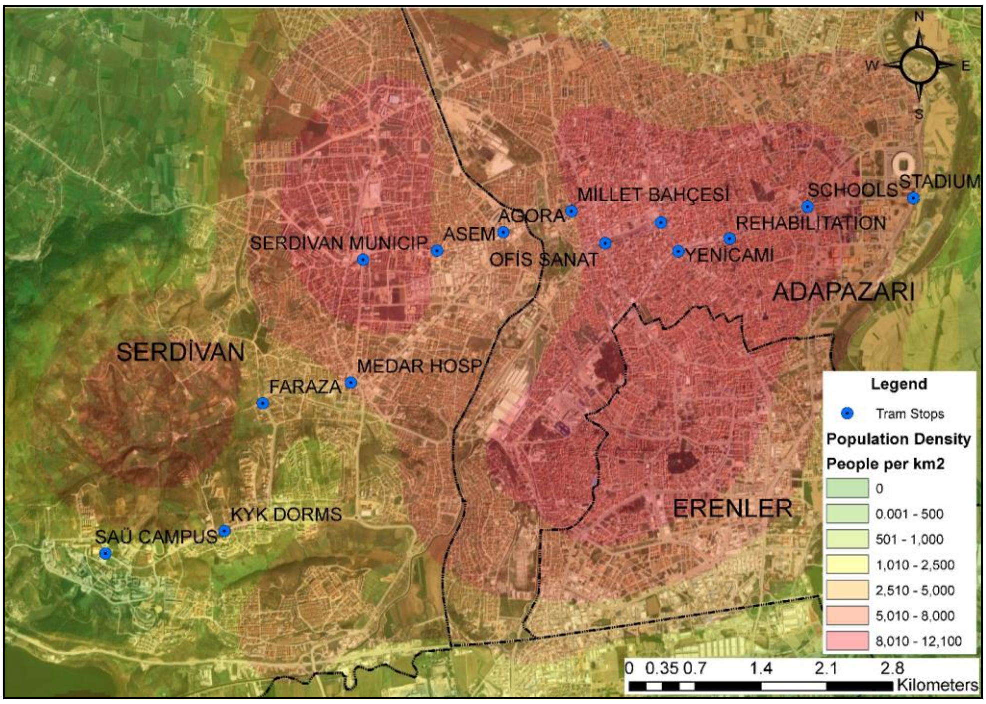

Figure 6. Population density with basemap.

Table 2. Population densities and areas of stops both bus and tram.

Tram Stops	**Neighborhood Name**	**Popul. of Neighb. (people)**	**Area of Neighb. (km^2)**	**Pop. Density of Neighb. of Tram Stop (people/km^2)**	**Pop.Density (people/km^2)**
SAÜ Campus	Esentepe	4354	7.0741	615.488	1029.797
KYK Dorms	Kemalpaşa	30149	11.6237	2595.985	2570.615
Faraza	Kemalpaşa	30149	11.6237	2595.985	4084.053
Medar Hospital	Kemalpaşa	30149	11.6237	2595.985	5303.837
Serdivan Municip.	İstiklal	23626	3.5552	6645.501	10404.915
ASEM	İstiklal	23626	3.5552	6645.501	7709.966
Agora	İstiklal	23626	3.5552	6645.501	5410.658
Millet Bahçesi	Semerciler	5139	0.5172	9936.699	7927.332
Ofis Sanat	Semerciler	5139	0.5172	9936.699	9261.011
Demokrasi Square	Semerciler	5139	0.5172	9936.699	10771.282
Yenicami	Yenicami	1636	0.1290	12680.517	11728.125
Rehabilitation	Yenigün	14288	0.8503	16803.122	12039.357
Schools	Yağcilar	22468	3.0455	7377.427	10261.959
Stadium	Yağcilar	22468	3.0455	7377.427	5249.953

It is seen that the new tram line covers the high population density areas as expected. However, it is notable that the SAÜ Campus and KYK Dorms are not presented as high population density areas. This is because the students are mostly not registered in the campus area due to inefficiencies in the data gathering of TUİK for temporary occasions. Therefore, considering nearly 50 thousand active students on the campus, these two stations will also be heavily used in the area.

Tram stations and Bus Lines (BL) overlap at some points. Some of BL are almost in the same direction and service the same area to carry passengers. Line-4 and Line-15 intersect with most of the Tram Stops. These lines should be revised not to be an alternative to tram lines but as a supplementary to enhance the connectivity and distribution of the passenger load. Thus, the overlapping bus lines could be optimized depending on the travel demand and tram frequency of daily trips. Some of the BLs also touch on the Tram Stops such as 26 BTL intersecting on "Ofis Sanat" (**Table 3**). The maximum number of intersecting points is "Ofis Sanat", and "Ofis Sanat Tram Stop" has also four (more parallel lines with tram lines) bus transit lines, which are called Line-4, Line-15, Line-19K, and Line-27. It can be said that "Ofis Sanat" can be a HUB Stop and Transit Point for both trams and buses. Bus Lines and Tram Stops intersect more on "Ofis Sanat and Demokrasi Square". The Density Map is more concentrated in areas close to "Demokrasi Square" and "Ofis Sanat" Stops (**Figure 7**). It means that the BLs are denser on both stops than the others. The areas on the Density Map show that it becomes more concentrated from green to red. The redder the map, the denser the BLs are through that area.

Table 3. Number of bus lines (BL) passing through the Tram Stops and the status of the BL passing through tram stops the most (X represents the overlap of bus lines with tram lines and stations).

Tram Stops	Number of BTL Passing through the Tram Stops	Line-4	Line-15	Line-19K	Line-27
SAÜ Campus	11	X	X	X	X
Kyk Dorms	11	X	X	X	X
Faraza	3				
Medar Hospital	3				
Serdivan Municip	6	X			X
ASEM	6	X		X	X
Agora	9	X		X	X
Millet Bahçesi	12				
Ofis Sanat	26	X	X	X	X
Demokrasi Square	19	X	X	X	
Yenicami	5	X	X	X	
Rehabilitation	2		X		
Schools	2		X		
Stadium	1		X		

Figure 7 shows the 26 bus lines operated by Sakarya Metropolitan Municipality, the planned tram line, the stations that will serve on this line, and the density distribution of these stops along the route. The figure shows that a great number of bus routes pass through the Central Business District (CBD) area, where the bus stop

density is high. In addition, the presence of the main bus route (Ofis Sanat) and the intercity train station belonging to the routes within this area is also very important in terms of multimodal integration.

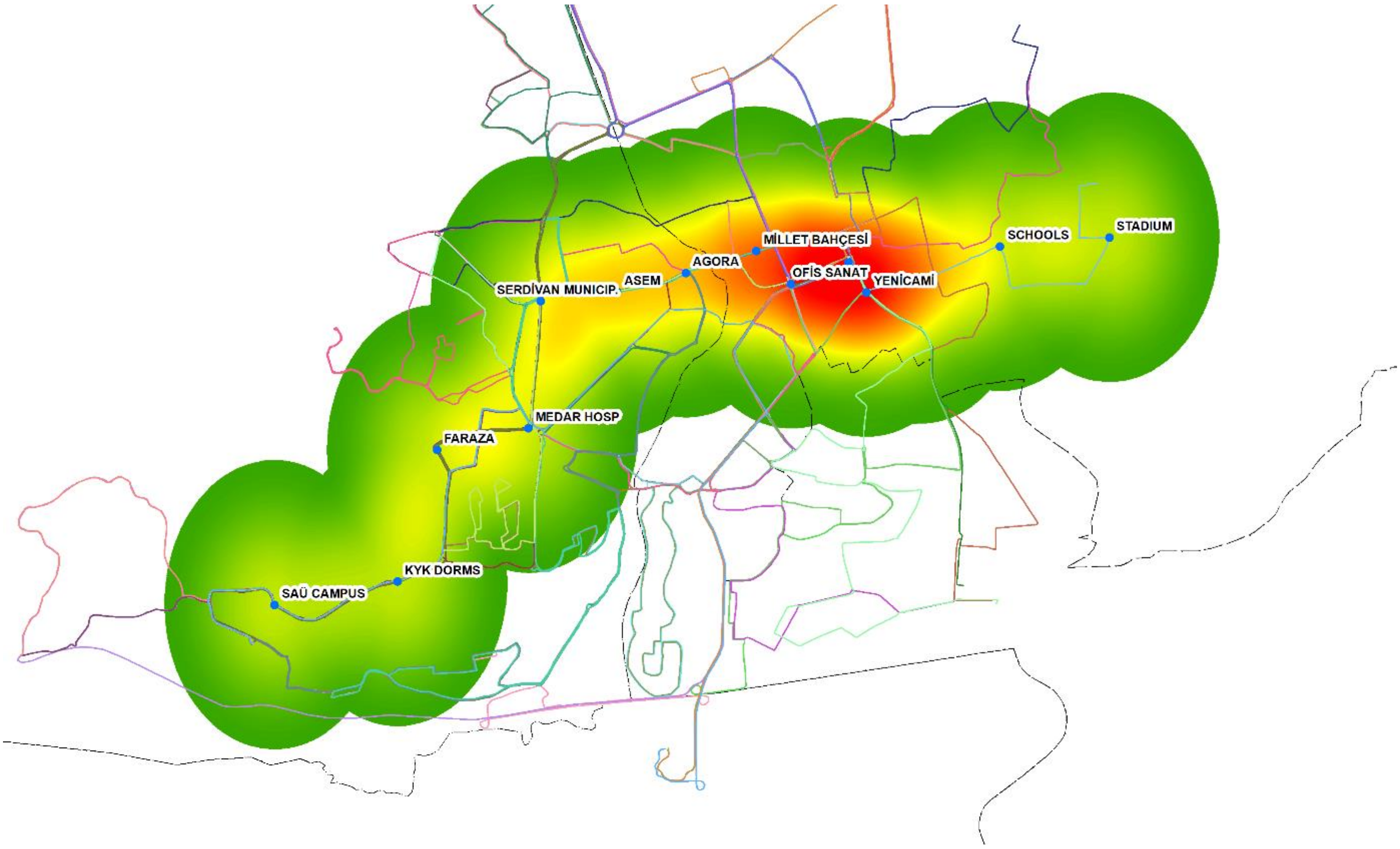

Figure 7. Tram stations and bus lines (BL) density map.

In short, the number of 26 Bus Lines (BL) and 1571 bus stops were analyzed according to the planned 3-phase tram line and planned tram stops. Since the planned tram-line project on Phase-1 and part of Phase-3 draws a linear direction that will connect between the east and west of the city, the tram line network examined includes the entire Phase-1 and part of Phase-3. Some of BTL were seen to operate in parallel with the planned tram line. 14 tram stops are analyzed, and BLs with 6 or more overlapping points in common with the tram line have been detected. These BL need to be optimized once the tram line projects are completed. While the locations of bus stops need to be optimized at some points, BL needs to be optimized depending on passenger density on the streets. After the tram project is completed, a more precise optimization can be made after passenger behavior is included in the analysis.

4. Discussion and conclusion

The results of this study underscore the significant potential for newly planned tram lines to enhance walkability and accessibility within Sakarya, offering important insights into urban mobility planning. Through Geographic Information Systems (GIS) analysis, we have delineated the catchment areas for proposed tram stops and assessed the integration with existing public transport routes. This analysis highlights several key findings and implications, which align with and expand upon existing literature in the field of urban mobility.

One critical observation is that the new tram lines will indeed enhance accessibility by increasing the proportion of the population within walking distance of public transport. However, it is important to note that trams and buses serve different functions in an integrated transport network. As highlighted by Vuchic [54], buses often serve as feeder services for trams or cover areas that fall between tram lines, especially in suburban or outer-city areas. Moreover, buses and trams differ significantly in terms of capacity, frequency, scheduling, and pricing, as documented by Cervero and Duncan [55], which are essential considerations when optimizing public transport networks. The aim of this study is not to suggest that buses and trams are redundant or mutually exclusive, but rather to identify opportunities for optimizing intersections where tram and bus stops are located in close proximity. This could reduce service redundancies and improve network efficiency by minimizing overlaps that lead to inefficiencies in high-density areas. By refining bus routes to complement the tram network, planners can improve overall system integration, as supported by research on multimodal transportation systems [56].

Furthermore, while this study has focused primarily on time-oriented accessibility, it is essential to consider additional factors such as origin-destination patterns, which are critical for informed transport planning. For instance, the spatial distribution of student accommodations—whether students live on or off-campus—plays a key role in determining transport demand. A significant body of literature, including works by Loo et al. [57], emphasizes the importance of understanding travel patterns, particularly in the context of university campuses and other areas with high transit demand. In this regard, the findings of this study, particularly around the SAÜ Campus and KYK Dorms, are only partial in that they do not account for the full extent of where students live and how this impacts overall demand for tram and bus services. Future research should integrate more comprehensive data on travel patterns, using origin-destination surveys or models to provide a fuller picture of transport network usage [58].

Considering the trip chain, the relationship between buses and trams can indeed be both competitive and complementary, depending on the context and design of the transport network. In central areas with high demand, buses and trams may operate competitively due to overlapping service areas, as both aim to connect passengers to key destinations. However, as literature on multimodal transport networks suggests, these modes can also complement each other by serving different functions within the trip chain [55,56]. For example, buses may act as feeders to tram lines, especially in peripheral areas where tram coverage is limited. By efficiently integrating bus and tram schedules and routes, planners can ensure that each mode serves a distinct role in the trip chain—buses providing local access and trams handling higher-capacity, longer-distance travel. This complementary relationship helps to create a seamless travel experience, reduces redundancy, and increases the overall efficiency of the network. The results of our study highlight opportunities for optimizing this integration in Sakarya, and further research should explore the dynamics between bus and tram systems, particularly how they influence travel patterns and trip chains in different urban contexts.

In conclusion, this study confirms that the planned tram lines will substantially improve public transport accessibility and walkability in Sakarya by serving a wide range of high-density areas. Optimizing the integration of tram and bus services will be crucial in creating a more cohesive and efficient network, particularly by addressing redundant routes in central areas. The key findings include:

1) The proposed tram lines will enhance walkability by reducing the distance residents need to travel to access public transport, with significant portions of the population being within 5 to 10-minute walking distances from tram stops.
2) Existing bus routes show considerable overlap with tram stops, indicating areas where service optimization is needed to avoid redundancies and enhance overall network efficiency. These optimizations can improve the complementarity of tram and bus services rather than replacing one with the other [55].
3) High-density population areas are well-served by the planned tram system, though further adjustments are needed to account for temporary and transient populations, such as students, particularly considering origin-destination patterns and transport demand [57].

The results offer valuable insights for urban planners and decision-makers in Sakarya, highlighting the need to optimize public transport networks by integrating different modes of transport effectively. Implementing these recommendations can lead to a more efficient, accessible, and sustainable public transport system in Sakarya. Future research should further refine the analysis by incorporating real-time transit data and a deeper examination of pedestrian infrastructure and travel patterns.

5. Current limitations

While this study provides valuable insights into the impact of planned tram lines on walkability and accessibility in Sakarya, it primarily focuses on time-based catchment areas, which may not fully capture the complexity of accessibility. Walkability and accessibility are multidimensional concepts that extend beyond mere proximity to transit services. Factors such as pedestrian safety, terrain, micro-climate, and the quality of pedestrian infrastructure significantly influence how easily and safely individuals can access public transport. For instance, a 10-minute walking distance may be less feasible for individuals with mobility impairments if sidewalks are poorly maintained or if steep inclines are present. Likewise, adverse weather conditions or insufficient shelter along pedestrian routes could diminish the accessibility of tram stops. Although this study acknowledges these factors as relevant to urban mobility, they were not directly analyzed due to the complexity of obtaining detailed, location-specific data on each aspect.

Additionally, cost factors, such as the affordability of tram services compared to other modes of transportation, were not considered in this analysis, nor was the subjective perception of safety during pedestrian trips. These are crucial components of a holistic understanding of walkability and accessibility but were beyond the scope of the current GIS-based approach. Future research could incorporate these elements by using qualitative data collection methods, such as surveys, or by integrating additional datasets related to terrain, pedestrian safety, and infrastructure quality. This would allow for a more comprehensive evaluation of how tram lines impact urban mobility, particularly for vulnerable populations who might face greater barriers to accessing public transport.

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