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Spatiotemporal Analysis and Evaluation of Passenger Flows in Diagnosing the Operational Efficiency of Public Transport – A Case Study of a Local Bus System

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Mariusz Sowa[1]

Abstract:

Purpose: *Public transport systems in suburban areas face a fundamental challenge of maintaining a balance between maximising service accessibility and ensuring an efficient allocation of public funds. Operational efficiency in peripheral zones is often constrained by low population density and the dominance of commuter traffic, which leads to uneven vehicle utilisation and temporal imbalances in passenger flows. The aim of this study is to perform a spatiotemporal analysis and evaluation of passenger flows as a diagnostic tool for verifying the adequacy of transport supply relative to demand within a selected local bus network.*
Design/Methodology/Approach: *The research adopted an empirical and diagnostic approach. Passenger movement data were collected through direct field observation of boarding and alighting passengers on the main bus lines serving a suburban municipality over a full weekly cycle, encompassing both weekdays and weekends. The collected data were subjected to a detailed spatiotemporal analysis in order to identify daily load profiles, peak demand hours, and spatial concentration zones of passenger activity.*
Findings: *The results revealed a pronounced directional asymmetry in passenger flows, characterised by dominant morning peak demand (06:00–08:00) and a clear imbalance between inbound and outbound traffic. Approximately 70% of total passenger movement was concentrated within three major suburban settlements. During the morning peak, vehicle occupancy levels reached 65–70% of total capacity, whereas off-peak and weekend periods were marked by significant declines in utilisation, indicating inefficient deployment of service resources. The analysis also showed that internal (intra-municipal) trips increased by an average of 10 percentage points during weekends, suggesting a functional shift in mobility patterns over the weekly cycle.*
Practical Implications: *The findings provide empirical evidence of operational patterns typical of peripheral transport systems and highlight the diagnostic potential of spatiotemporal analysis for identifying structural inefficiencies. The study indicates that the key direction for improvement involves differentiated service provision, including variable service frequency and flexible fleet allocation with smaller-capacity vehicles during low-demand periods. Enhanced fare and timetable integration with urban transport systems is also recommended.*
Originality/Value: *This research contributes original empirical insights into the operational efficiency of local public transport systems and offers a practical analytical framework to support evidence-based decision-making and sustainable mobility planning.*

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[1]*University of Szczecin, Faculty of Economics, Finance and Management, Szczecin, Poland, e-mail: mariusz.sowa@usz.edu.pl;*

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1. Introduction

Public transport plays a fundamental role within both urban and logistical systems, constituting a key element integrating processes related to the movement of people and serving as an essential condition for economic development and social mobility. In the context of sustainable regional development, public transport is an integral component of the overall transport system, offering an alternative to individual car use and thereby contributing to the reduction of congestion and pollutant emissions.

Under conditions of increasing suburbanisation and diversification of settlement structures, maintaining the operational efficiency of public transport systems has become a major challenge from both planning and management perspectives. In particular, bus networks serving dispersed settlement areas must balance service accessibility for residents of smaller localities with the economic rationality of service provision and the need to ensure acceptable vehicle occupancy levels.

The efficiency of public transport service delivery represents a key determinant of the sustainability and functionality of local transport systems. Each local transport network faces a dual objective: on the one hand, to meet residents' mobility needs in an optimal way, and on the other, to ensure the rational allocation of public resources.

The research problem addressed in this article focuses on a suburban municipality located in north-western Poland, characterised by a distinct spatial dichotomy. On the one hand, suburbanisation in the largest residential areas generates regular and high-intensity passenger flows. On the other, the necessity to provide services for dispersed rural settlements hinders the establishment of optimal routes and timetables, creating a significant challenge in ensuring both accessibility and operational efficiency.

Consequently, maintaining a rational balance between economic viability and service availability becomes a key issue in the management of local public transport.

In the relevant literature, spatiotemporal analyses of passenger flows have gained increasing attention as an effective diagnostic tool for evaluating the functioning of transport systems. This approach enables the identification of mobility patterns across spatial and temporal dimensions, the detection of peak-hour concentrations and local demand "hotspots," as well as the assessment of service utilisation at the level of individual routes and stops.

The outcomes of such analyses provide an empirical basis for both operational decisions—such as adjusting service frequency and fleet allocation—and strategic planning, including route optimisation and integration with other modes of transport.

The objective of this article is to conduct a spatiotemporal analysis and evaluation of passenger flows in the context of diagnosing the operational efficiency of a public transport system, using the example of a selected local bus network. Accordingly, the key research question is as follows: *How does spatiotemporal analysis of passenger flows enable the quantification and evaluation of the operational efficiency of a local public transport system under conditions of spatial dichotomy?*

The study is based on direct passenger flow measurements (counting boarding and alighting passengers — IN/OUT) carried out over the full daily cycle for three bus lines serving the analysed area. Field data were collected between 3 and 16 June 2025, and the analysis includes demand distribution across two-hour intervals, the internal travel structure within the area, and vehicle occupancy estimates for individual routes and stops.

Based on these findings, conclusions regarding line performance and recommendations of both operational and planning nature are formulated. In addition, the study addresses a series of supporting research questions:

What are the spatiotemporal patterns of passenger flows in the analysed local bus system (distribution by time intervals, days of the week, and localities)? Which routes and stops generate the highest load (hotspots), and during which times of day do demand peaks occur? To what extent do existing routes ensure effective utilisation of the vehicle fleet (occupancy rates) within the current route network? What operational and planning recommendations can be formulated based on the analytical results, taking into account the balance between accessibility and cost efficiency?

An empirical approach was applied, based on direct observation and complemented by statistical and spatial analyses of passenger flow distributions. It should be noted that the adopted research procedure has certain limitations: the study was conducted over a relatively short, single-year period (one week following the end of the school year and at the beginning of the summer season), which may influence observed demand variations associated with seasonality and changes in school-related travel patterns.

Therefore, the results should be interpreted as a representative snapshot of the system's state during the analysed period, with a recommendation to conduct complementary seasonal measurements prior to implementing permanent network adjustments.

This study contributes both practical and methodological value to the field of transport sciences. The practical contribution lies in providing an analytical framework based on field data aimed at validating the operational performance of the public transport system.

The results — including the identification of mobility patterns (such as peak hours and local demand hotspots) and the estimation of vehicle occupancy levels — constitute a direct basis for administrative and planning decisions. The overarching objective is to optimise the bus route network, enhance the attractiveness of public transport as an alternative to private car use, and ensure a more efficient allocation of public resources.

From a methodological perspective, the study demonstrates the applicability of spatiotemporal analysis of passenger flows for the operational diagnosis of public transport performance. The proposed research model can serve as a reference framework for similar studies in other municipalities, supporting decision-making processes in the areas of transport planning, mobility policy, and sustainable development of communication systems.

2. Literature Review

Research on the efficiency of public transport systems constitutes a broad and evolving stream within the field of transport economics and urban studies. In recent years, attention has increasingly shifted towards the integration of operational, spatial, and behavioural dimensions in the assessment of system performance (Brons *et al.,* 2005; Eboli and Mazzulla, 2012).

Classical studies demonstrated that system efficiency cannot be evaluated solely through quantitative supply metrics or capacity utilisation, but must also account for socio-spatial disparities and equity of access (Currie, 2010; Pojani and Stead, 2017). In this context, Pojani and Stead (2017) emphasised that transport networks in developing or rapidly urbanising areas often face structural inefficiencies resulting from uncoordinated spatial growth.

The allocation of public resources is frequently assessed through methods such as Data Envelopment Analysis (DEA), which serve to evaluate the technical and operational efficiency of transport operators (Yu *et al.,* 2024; Brons *et al.,* 2005). Such quantitative approaches enable benchmarking of relative performance across spatial contexts, providing a methodological foundation for assessing technical and cost efficiency in local systems.

A central theme in contemporary transport diagnostics is the spatiotemporal analysis of passenger demand, which allows for a dynamic examination of demand patterns and operational bottlenecks. Jiao and Cai (2020) demonstrated the potential of GIS-based accessibility modelling for identifying “transit deserts,” while more recent studies (Lv *et al.,* 2024; Guo *et al.,* 2024) have applied advanced geoinformation models to investigate temporal variability and accessibility equity.

This research strand is particularly relevant to the present study, as it facilitates the diagnosis of spatiotemporal asymmetry in passenger flows—one of the key challenges in suburban transport systems. Empirical findings (Li *et al.,* 2024; Abuaisha and Abu-Eisheh, 2023) highlight that directional and temporal asymmetry in vehicle occupancy represents a major source of reduced operational efficiency, calling for dynamic and adaptive fleet management. The use of spatiotemporal methods enables not only the analysis of passenger flow dynamics but also the prediction of future demand variations based on seasonal and structural factors.

A parallel research stream focuses on the operational and managerial dimensions of public transport systems. Agrawal *et al.* (2020) and Yu *et al.* (2024) proposed frequency optimisation models integrating timetable design with dynamic demand parameters. These studies complement research on fleet size optimisation (Abuaisha and Abu-Eisheh, 2023) as a determinant of system reliability and cost efficiency.

Furthermore, Cheng *et al.* (2024) and Wu *et al.* (2024) employed machine-learning techniques and smart-card data to capture spatiotemporal variations in passenger behaviour and to predict flows with greater accuracy—directly supporting effective fleet allocation and service planning. Such approaches provide the analytical basis for the design of flexible fleet management models applicable in systems characterised by heterogeneous demand densities.

From a governance and social perspective, Kębłowski (2018) conceptualised public transport as a “common good,” emphasising the dimensions of social equity and inclusiveness within mobility systems. In the Polish context, Sołtysik *et al.* (2017) and Beim *et al.* (2019) offered empirical analyses of passenger exchange times and public transport accessibility in medium-sized cities, serving as benchmarks for assessing the operational efficiency of local bus networks. Papadakis *et al.* (2024) positioned these analytical advances within the broader framework of sustainable urban mobility, arguing that the integration of spatial diagnostics with efficiency evaluation is crucial for adaptive planning in suburban and peripheral areas.

In summary, contemporary literature highlights the necessity of integrating quantitative, spatial, and social approaches in the process of diagnosing and optimising the functioning of local public transport systems. The convergence of these three perspectives provides a comprehensive foundation for developing efficiency assessment methods that can effectively support decision-making in sustainable mobility planning.

Furthermore, the findings of the literature review confirm that the assessment of public transport efficiency requires the integration of quantitative and spatial approaches, with particular emphasis on empirical studies based on passenger flow data and vehicle occupancy analysis. The present study follows this research direction by developing practical diagnostic tools at the micro scale, which can be applied in the planning and evaluation of local bus transport systems.

3. Research Methodology

To assess the operational efficiency of the public transport system, an empirical research method based on direct measurement of passenger flows was applied. The adopted procedure enabled a detailed spatiotemporal analysis of passenger movement and verification of vehicle utilisation indicators for individual lines and services. This approach made it possible not only to identify mobility patterns but also to determine the degree of operational efficiency of the system under real demand conditions.

The primary objective of the research was to obtain objective quantitative data on passenger traffic intensity and passenger exchange at individual stops, across different times of the day and days of the week. These data formed the basis for diagnosing the level of public transport utilisation, identifying areas of highest demand (hotspots), and evaluating the operational performance of particular routes. The methodology was designed to ensure the comparability of results in future periodic studies and to allow their potential use in demand modelling for public transport.

The research object was the bus transport system operating within a suburban municipality in north-western Poland, with particular attention to lines serving the main passenger flows generated in the suburban zone of the Szczecin metropolitan area. The study covered three key bus routes — Line 241, Line 242, and Line 243 — whose trajectories and timetables were analysed in terms of their adequacy to actual transport demand.

These bus lines differ in route length, service frequency, and spatial configuration of stops, which allowed for a comparative assessment of their efficiency under diverse operational conditions. The spatial scope included both suburban localities generating intensive passenger flows and dispersed residential areas, where demand for public transport services is lower and more irregular.

A direct measurement method was employed, consisting in the systematic recording of the number of boarding (IN) and alighting (OUT) passengers at successive bus stops along the routes of the surveyed lines. Observers, positioned inside the vehicles, conducted systematic counts during each service run within the study period. The data were recorded in specially prepared observation sheets that allowed for the simultaneous registration of location, time, service number, and passenger count.

The choice of this method was motivated by its high level of accuracy, the minimisation of indirect measurement errors, and the possibility of directly linking passenger counts with specific operational conditions. The research procedure was carried out in four consecutive stages:

Stage 1 involved the establishment of the research framework. The key element was the precise formulation of specific objectives and research hypotheses derived from the main research question. Operational definitions of efficiency indicators were developed (e.g., service utilisation ratio, vehicle occupancy rate). In parallel, the observation area was delimited, focusing on the key segments of the three selected bus lines (241, 242, 243) within the municipality. Measurement protocols and observation sheets were prepared as standardised tools for field data collection, and a detailed fieldwork schedule (dates and service hours) was established. The final step consisted of the recruitment and training of field observers to ensure the consistency and objectivity of data recording procedures.

Stage 2 comprised the implementation of the empirical data collection procedure. This phase involved synchronous, direct recording of passenger streams by trained observers. At each stop along the surveyed lines, for every scheduled service run, the number of boarding and alighting passengers was recorded, allowing dynamic tracking of passenger loads along each inter-stop section. The systematic acquisition of data was carried out according to a strict temporal and spatial regime, covering both weekdays (peak-hour operations) and weekends.

Stage 3 covered the processing and analysis of the collected data. The field data underwent quality verification to ensure the completeness and consistency of observation sheets. Subsequently, the datasets were entered into an analytical environment (specialised database or statistical software). The main task was to conduct a spatiotemporal analysis — developing passenger frequency distributions with respect to the time axis (daily and weekly profiles) and spatial axis (locations of the most heavily loaded stops). Vehicle occupancy indicators and other service utilisation metrics were calculated to provide an objective evaluation of system performance.

Stage 4 focused on the statistical interpretation and substantive synthesis of the obtained results. Patterns of residents' mobility were identified and characterised, taking into account variations in passenger flows by time of day and day of the week. Based on these findings, the adequacy of the current route network and timetable in relation to actual passenger demand was assessed. The outcome of this phase included the formulation of scientific conclusions and specific operational and planning recommendations for the public bus service operator, aimed at optimising service schedules and improving the functional efficiency of the system.

To visualise the results, passenger flow density maps and summary charts of passenger numbers by day of the week were used. These datasets served as the basis for calculating vehicle occupancy rates and identifying peak hours and the most heavily loaded stops.

It should be emphasised that the research was conducted after the end of the school year and at the beginning of the summer season, which may have contributed to a reduced level of demand from pupils and students.

Therefore, the obtained results should be regarded as representative of the analysed period, with a recommendation to extend future studies to other times of the year in order to capture potential seasonal and calendar-related effects. Despite these limitations, the applied method enabled the collection of reliable empirical data, allowing for a credible operational diagnosis of the public transport system.

4. Research Results and Discussion

4.1 Passenger Flow Characteristics

The aim of the conducted study was to determine the operational efficiency of the local public transport system through a spatiotemporal analysis of passenger flow patterns across three bus lines with diverse spatial and functional structures. The collected empirical data made it possible to identify the dynamics of mobility within daily and weekly time frames, as well as to analyse the degree of vehicle utilisation and the spatial distribution of demand across individual settlements.

In total, more than 4,900 passenger trips were recorded during the study period, with the vast majority occurring on weekdays. On average, over 3,200 trips were registered on working days, around 1,000 on Saturdays, and approximately 700 on Sundays.

As presented in Table 1, the dominant share of passenger traffic is associated with weekday travel, which confirms the strong linkage between transport demand and the daily rhythms of residents' occupational and educational activities.

The dynamics of passenger flows in daily and weekly terms exhibit significant variability. On weekdays, the average daily ridership across the analysed bus lines reached 3,232 passengers, with a clear directional asymmetry — 1,720 boardings within the municipality compared to 1,512 alightings. During non-working days, a substantial decline in demand was observed: 1,003 trips on Saturdays and 717 trips on Sundays.

Table 1. *Average number of passengers using public bus transport services in the surveyed routes at different time intervals*

Departure Time	**Weekdays**			**Saturday**			**Sunday**		
	IN	OUT	**SUM**	IN	OUT	**SUM**	IN	OUT	**SUM**
04:00 - 06:00	88	51	**139**	19	21	**40**	5	9	**14**
06:00 - 08:00	467	316	**783**	55	62	**117**	45	32	**77**
08:00 - 10:00	225	163	**388**	88	49	**137**	66	68	**134**
10:00 - 12:00	91	78	**169**	26	15	**41**	15	21	**36**
12:00 - 14:00	177	137	**314**	17	23	**40**	41	32	**73**
14:00 - 16:00	254	306	**560**	124	135	**259**	84	70	**154**
16:00 - 18:00	222	257	**479**	52	68	**120**	59	65	**124**
18:00 - 20:00	147	113	**260**	78	93	**171**	35	39	**74**
20:00 - 22:00	39	75	**114**	26	52	**78**	10	21	**31**
22:00 - 24:00	10	16	**26**	0	0	**0**	0	0	**0**
SUM	**1720**	**1512**	**3232**	**485**	**518**	**1003**	**360**	**357**	**717**

Source: *Author's calculations.*

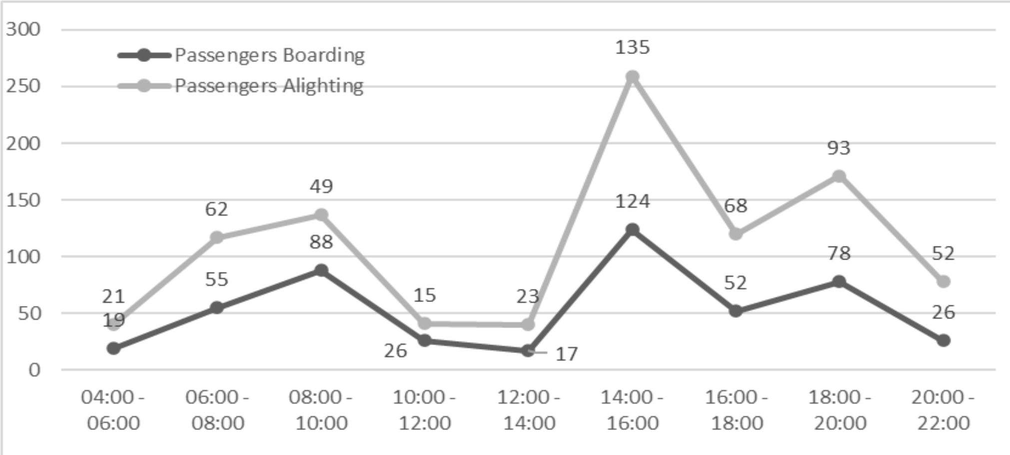
A key observation concerns the shift in temporal demand profiles. Weekdays are dominated by a pronounced morning peak (06:00–08:00), with an average of 783 trips, representing a seven- to tenfold increase compared to weekend levels. On Saturdays and Sundays, the centre of mobility shifts toward afternoon hours (after 14:00). Regardless of the day of the week, a marked decrease in public transport demand was recorded after 20:00.

The daily structure reveals two distinct ridership peaks: a morning peak (06:00–08:00) and an afternoon peak (14:00–16:00). Figure 1 presents the hourly distribution of passenger flows on weekdays. Two pronounced peaks of mobility are visible, largely corresponding to the typical starting and finishing hours of work and school activities.

Figure 1 illustrates a clear concentration of passenger demand during the morning and afternoon peaks, confirming the dominance of commuting-related mobility patterns.

The analysis of the daily passenger flow profile (Figure 1) clearly indicates a concentration of maximum ridership during the morning peak period (06:00–08:00). This time segment records the highest absolute number of trips on weekdays. A key observation concerns the pronounced directional asymmetry between the number of boardings (467 passengers) and alightings (316 passengers) at stops located within the municipality. This is the largest imbalance among all time intervals, reflecting the commuting-dominated character of passenger movement from the suburban areas of the municipality toward the metropolitan centre.

Figure 1. *Average number of passengers using public bus transport services on weekdays (Mon–Fri) across different time intervals*



Source: *Own elaboration.*

The afternoon peak (14:00–16:00) exhibits lower intensity compared to the morning peak, followed by a systematic decline in both boardings and alightings. The persistence of this downward trend after 20:00 indicates a vanishing evening demand, suggesting the potential for rationalising service supply in later hours to improve operational cost efficiency.

4.2 Spatial Structure of Passenger Mobility

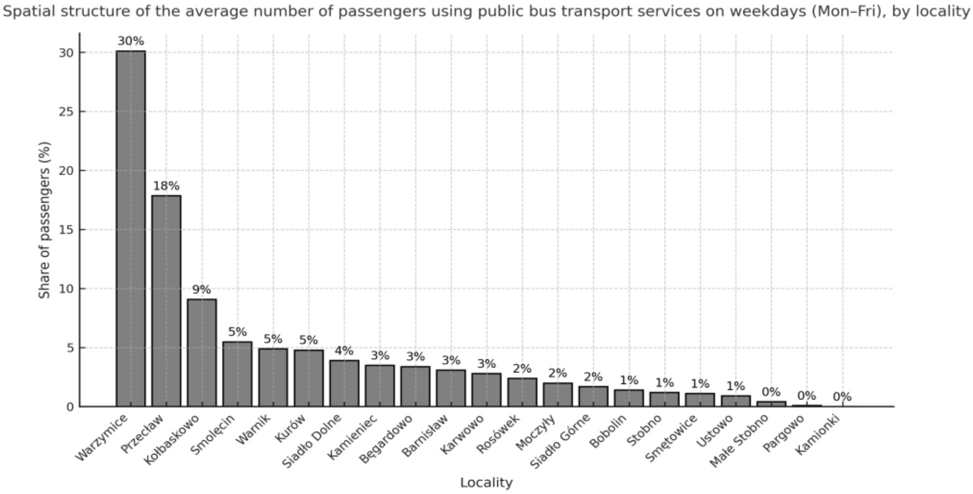
In spatial terms, three localities dominate, jointly generating approximately 70% of total passenger traffic — two with a suburban character and one serving as the central administrative settlement.

The spatial distribution of passenger flows is presented in Figure 2, which illustrates the variation in travel intensity between localities on weekdays. The highest passenger volumes are observed in areas situated closer to the city boundary and near the main transport hubs, reflecting the strong functional linkages between suburban zones and the metropolitan core.

According to the data presented in Figure 2, the spatial structure of demand for public transport services is characterised by a high degree of concentration in only three key localities. In total, 70% of all trips are generated by passengers using stops located in Przecław (30%), Warzymice (24%), and Kołbaskowo (16%).

These locations constitute the main traffic generators, directly reflecting suburbanisation processes and the concentration of population within the area.

Figure 2. *Spatial structure of the average number of passengers using public bus transport services on weekdays (Mon–Fri), by locality*



Source: *Author's calculations.*

The remaining localities exhibit a marginal share in the overall passenger load. Settlements such as Kamieniec, Kurów, and Siadło Dolne each account for only 4%, while Bęgardowo generates approximately 3% of total passengers. The shares of other villages do not exceed 2%, classifying them as low-demand segments of the network and suggesting the need for a differentiated service strategy aimed at optimising operational costs.

Table 2 presents the distribution of internal trips by bus line and time interval. The data confirm that morning and afternoon periods are dominated by intra-municipal journeys, whereas evening hours are characterised by an increase in inter-municipal connections.

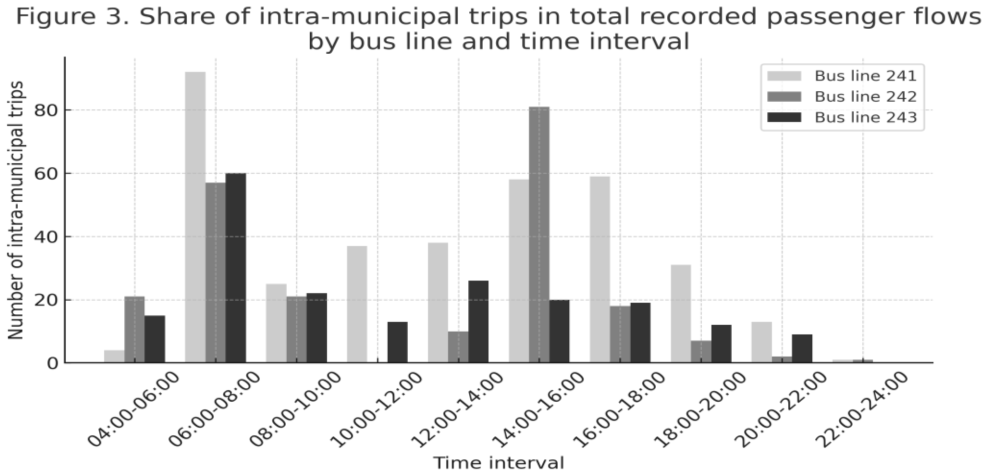
Table 2. *Intra-municipal trips by bus line and time interval*

Departure Time					**Saturday**				**Sunday**			
	Line 241	**Line 242**	**Line 243**	**Sum**	**Line 241**	**Line 242**	**Line 243**	**Sum**	**Line 241**	**Line 242**	**Line 243**	**Sum**
04:00-06:00	4	21	15	**40**	8	6	6	**20**	1	1	0	**2**
06:00-08:00	92	57	60	**209**	11	8	8	**27**	27	8	6	**41**
08:00-10:00	25	21	22	**68**	0	25	25	**50**	34	0	16	**50**
10:00-12:00	37	0	13	**50**	0	8	8	**16**	0	0	5	**5**
12:00-14:00	38	10	26	**74**	0	8	8	**16**	8	0	13	**21**
14:00-16:00	58	81	20	**159**	12	20	20	**52**	25	17	7	**49**
16:00-18:00	59	18	19	**96**	0	8	8	**16**	32	13	1	**46**
18:00-20:00	31	7	12	**50**	7	15	15	**37**	18	2	11	**31**
20:00-22:00	13	2	9	**24**	3	18	18	**39**	0	0	1	**1**
22:00-24:00	1	1	0	**2**	0	0	0	**0**	0	0	0	**0**
SUM	**358**	**218**	**196**	**772**	**41**	**116**	**116**	**273**	**145**	**41**	**60**	**246**

Source: *Author's calculations.*

Table 2 indicates that internal passenger movements are most intensive during the morning and afternoon peaks, reflecting the commuting character of the transport system. The percentage share of these intra-municipal trips in the total number of recorded journeys across the analysed routes is presented in Figure 3.

Figure 3. *Share of intra-municipal trips in total recorded passenger flows by bus line and time interval*



Source: *Author's calculations*.

These findings confirm the commuting nature of the transport system and underline the importance of demand-responsive service planning to maintain both operational efficiency and accessibility.

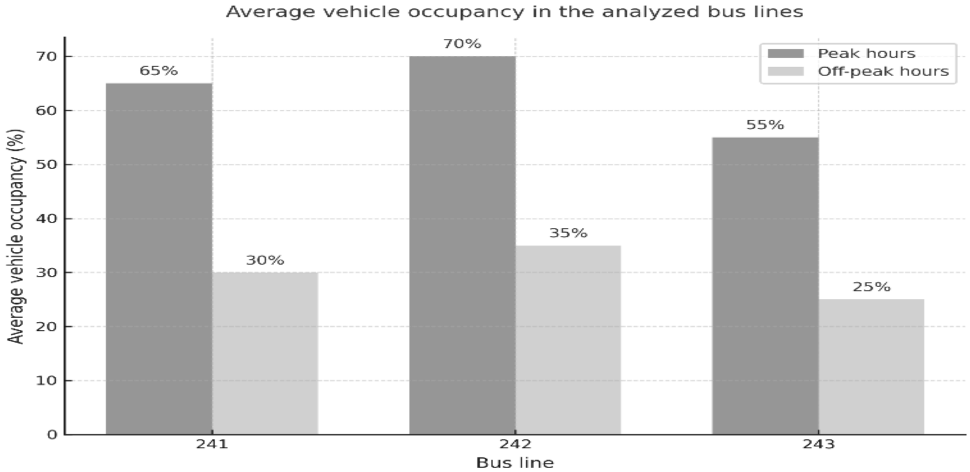
4.3 Vehicle Occupancy and Operational Efficiency

Bus occupancy represents a key indicator of the operational efficiency of the public transport system. A high level of vehicle utilisation contributes to the economic and environmental rationality of system performance, whereas low off-peak occupancies indicate areas of limited demand and potentially excessive service supply.

The empirical data analysis involved a comparison of three bus lines that differ in route length, number of stops, and spatial coverage. For the purpose of the study, an overview of average vehicle occupancy was developed for both peak and off-peak periods, enabling an assessment of capacity utilisation levels across individual lines and the identification of differences in operational performance.

As illustrated in Figure 4, during the morning and afternoon peaks, the highest level of vehicle occupancy was recorded on Line 242 (approximately 70%), followed by Line 241 (65%), and Line 243 (55%). Outside of peak hours, the average occupancy declined to 25–35%, indicating substantial variation in demand and capacity utilisation depending on the service zone.

Figure 4. *Average vehicle occupancy in the analysed bus lines*



Source: *Author's calculations.*

The asymmetry of passenger flows—with the number of boardings exceeding the number of alightings in the direction of the city—confirms the commuting function of the bus transport system. These results provide a rationale for revising the timetables and adjusting the frequency of services in the direction opposite to the main traffic stream. The observed differences between Lines 241 and 243 also indicate the need to optimise fleet deployment by aligning vehicle capacity with actual passenger demand.

The identified variation in occupancy levels highlights the necessity of adopting flexible planning strategies for service operations—particularly by adjusting service frequency to the diurnal rhythm of demand and deploying smaller-capacity vehicles during low-demand periods. From an operational perspective, this approach can contribute to reducing operating costs while maintaining the accessibility of public transport services across the entire service area. The findings outlined above form the empirical basis for the concluding remarks and recommendations presented in the following section.

5. Discussion

The results of the conducted study confirm the differentiated nature of demand for public transport services and the directional asymmetry of passenger flows depending on time of day and direction of travel. The observed traffic patterns indicate a commuting-dominated function of the system, concentrated on connections with the urban centre. The maximum vehicle occupancies during peak hours and the significant decline in passenger numbers during off-peak periods provide empirical confirmation of a peripheral transport pattern, typical of systems serving suburban zones.

The identified disparities between travel directions and between individual bus lines confirm the uneven utilisation of the vehicle fleet. Commuter-oriented lines (241, 242) exhibit higher occupancy rates and greater temporal variability throughout the day, whereas local lines (243) demonstrate a more stable but lower load profile. This distribution of demand implies the need to differentiate service frequencies and better match vehicle capacities to actual passenger flows.

The findings are consistent with conclusions from previous research, which indicate that the operational efficiency of suburban public transport systems is largely determined by the availability of alternative transport modes, the distance from the urban core, and the functional–spatial structure of the area (Pojani & Stead, 2017; Currie, 2020). The empirical evidence further suggests that maintaining the competitiveness of public transport relative to private car use depends on schedule stability, punctuality, and the adequacy of service supply to residents' daily activity patterns.

The combined analysis of vehicle occupancy and the spatial distribution of passenger flows allows for a precise diagnosis of the key directions for improvement. The identified mobility patterns provide a foundation for implementing flexible organisational measures, such as adjusting fleet size to the time of day, optimising the number of trips during low-demand periods, and introducing fare and timetable integration with the urban transport network.

From a planning perspective, the results provide strong arguments for reinforcing the integrative functions of public transport within the urban–suburban system and for expanding the use of empirical data in decision-making processes concerning service organisation and network design. The insights obtained form the empirical and analytical foundation for the conclusions and recommendations presented in the following section.

6. Conclusions, Proposals, Recommendations

The conducted empirical research enabled a comprehensive evaluation of the operational efficiency of the public transport system in a suburban area, taking into account both spatial and temporal dimensions. The analysis of passenger flows revealed a clear directional asymmetry and significant daily variability in traffic intensity, which are typical features of systems serving commuting relations with the urban core. It was confirmed that the highest passenger loads are concentrated along the main transport corridors, with vehicle occupancy during peak segments reaching 65-70%.

At the same time, a pronounced decline in utilisation during off-peak hours adversely affects the economic performance of the system. The spatial distribution of passenger flows indicates the necessity to balance the service offer in relation to local zones with differentiated demand density.

The empirical results demonstrate that the operational performance of suburban public transport systems is strongly dependent on the accurate alignment of service supply (timetables and vehicle capacity) with the daily activity rhythm of the population, as well as on the degree of organisational and fare integration with the urban transport network. The obtained results constitute an original contribution to the development of diagnostic and evaluative methods for assessing the operational efficiency of public transport in small territorial units, where dynamic yet low demand requires flexible planning approaches and resource optimization.

6.1 Proposals

The evaluation of the efficiency of public transport service provision must take into account the inherent duality of objectives faced by local government units. On the one hand, there exists an imperative to maximize social utility, defined as the optimal satisfaction of residents' mobility needs. On the other hand, it is necessary to rationalize the allocation of public funds dedicated to subsidising these services.

The divergence between these priorities—further reinforced by statutory obligations (e.g., counteracting transport exclusion and ensuring school transport services)—creates significant complexity in designing timetables that achieve full economic efficiency while maintaining a high level of service accessibility.

Based on the conducted spatiotemporal analysis and the identified mobility patterns, the following strategic and operational recommendations are proposed to enhance the functional efficiency of the system:

1. Differentiation of Service Supply:
   Introduce variable service frequencies depending on the time of day and passenger flow direction (e.g., increasing the number of trips towards the urban centre during the morning peak) to adequately respond to the empirically identified asymmetry of passenger flows.
2. Flexible Fleet Management:
   Implement a variable-capacity vehicle allocation model, employing smaller vehicles during low-demand periods (e.g., after 20:00 and on weekends), thereby reducing unit operational costs and improving resource efficiency.
3. Intermodal Integration:
   Achieve full fare and timetable integration with the metropolitan public transport system to enhance the coherence of the transport offer and ensure greater continuity of travel for passengers.
4. Optimisation of Transfer Connectivity:
   Improve transfer processes through precise timetable synchronisation and

reduction of passenger waiting times at interchange hubs, which is essential for increasing the overall attractiveness of public transport.

5. Data-Driven Decision-Making:
   Establish a system of regular passenger flow monitoring and use the resulting empirical data (on occupancy and spatial distribution) as a key instrument supporting strategic and operational planning in resource allocation and service management.

6.2 Recommendations

In light of the obtained results, it is justified to direct future research efforts towards the following domains, aimed at deepening the cognitive contribution to the field and further advancing the methodological tools for evaluating the efficiency of public transport systems:

- Integration of Seasonal and Weekend Dimensions. It is recommended to extend the analyses by conducting cyclical measurements of passenger flows, allowing for the capture of the full spectrum of seasonal variability and a comprehensive characterization of mobility patterns on non-working days. This approach will enable a more accurate validation of the match between transport service supply and the annual rhythm of residents' mobility.
- Cost-Effectiveness Analysis**.** It is advisable to integrate passenger flow data with information on operational and maintenance costs. This will allow for the quantification of the economic efficiency of individual routes and the identification of optimal relationships between cost and vehicle utilization.
- Spatial Modelling and Demand Forecasting**.** The application of advanced geospatial modelling methods will enable the forecasting of changes in demand for public transport services under different settlement development scenarios. This, in turn, will facilitate the design of transport solutions aligned with urban and demographic development trends.
- Real-Time Decision Support. It is recommended to develop and implement digital tools supporting the visualization and analysis of dynamic data, enabling real-time evaluation of transport system performance and the introduction of flexible operational adjustments in response to changing traffic conditions and passenger demand.
- Replacement of standard buses with smaller vehicles, which generate lower operating costs and are more economical in situations with a smaller number of passengers, taking into account potential cooperation with private operators (public–private partnership). The implementation of the proposed solution is justified by the fact that smaller vehicles entail reduced operating expenses and higher cost-efficiency under conditions of limited passenger demand. This approach focuses on optimising operational costs and enhancing the efficiency of public transport services.

Smaller vehicles can be more effectively adapted to fluctuating passenger flows, which allows for:

- Reduction of operating costs**:** Smaller vehicles are characterized by lower fuel consumption and reduced maintenance expenses, which leads to an overall decrease in the costs associated with the operation of the public transport system.
- More effective adjustment to passenger needs: On routes with lower passenger flow intensity, the use of smaller vehicles is more appropriate, as it allows for increased service frequency, thereby improving accessibility and user comfort for residents relying on public transport.
- Reduction of exhaust emissions**:** Smaller vehicles generally produce lower levels of emissions, providing environmental benefits and contributing to improved air quality within the municipality.
- Fleet management flexibility**:** The deployment of smaller vehicles enables more flexible scheduling and adaptation of timetables to actual passenger demand, resulting in enhanced operational efficiency of the transport system.

Implementation of a municipal bicycle system as an additional form of transport enabling travel from smaller villages within the municipality to transfer points.

- Public bicycle systems operate continuously, 24 hours a day, providing users with high flexibility to use them at any time of day or night, while modern mobile applications facilitate convenient bike rentals.
- Promotion of a carpooling system (a transport organization model in which several passengers travel in one private vehicle along the same route). This system enables more efficient use of transport resources, reduces travel costs for participants, and decreases road traffic intensity and exhaust emissions. Carpooling also promotes fuel savings and reduces road infrastructure wear. Modern technologies, such as mobile applications and online platforms, make it easier to coordinate and organize such shared rides.

The main limitation of the study was the availability of empirical data, which primarily covered weekday measurements and lacked comprehensive information on passenger flows within the transfer network. Despite these limitations, the obtained results provide a reliable basis for formulating practical conclusions and directions for further analyses.

The conducted research demonstrates that the spatiotemporal analysis of passenger flows is an effective diagnostic tool, allowing not only for the assessment of the operational efficiency of the system but also for supporting the design of more sustainable, flexible, and accessible forms of public mobility.

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