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Service Frequency Standards in Regional Bus Transport: A Comparative Analysis of Passenger Trip Rates in Poland and the Czech Republic

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Abstract

Service frequency is one of the key determinants of public transport attractiveness, yet empirical standards for regional bus services remain poorly defined. This study examines the relationship between the number of daily bus service pairs and regional public transport use using data from Poland and two Czech regions (the Plzeň Region and the Vysočina Region). Public transport use was analysed separately for adults and for children and young people using two original indicators. For adults, the logistic model provided the best fit, revealing a clear saturation effect. Despite substantial differences in the overall level of public transport use, the characteristic service frequency thresholds were remarkably similar across all analysed regions. The identified thresholds corresponded to approximately 4, 8, 12, and 20 daily bus service pairs and formed the basis for a five-level classification of regional bus service standards. For children and young people, the relationship was weaker, and no single functional form clearly outperformed the others. The proposed framework contributes to sustainable regional mobility by linking service provision with observed passenger use and by providing evidence-based reference levels for planning and evaluating regional bus services. The identified thresholds may support the development of evidence-based service standards that improve accessibility and avoid inefficient service provision, providing a practical basis for balancing passenger benefits and the efficient use of public transport resources.

Keywords: regional bus transport; public transport demand; sustainable mobility; service frequency; transport accessibility

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1. Introduction

Service frequency, alongside travel time, travel cost, reliability, and travel comfort, is widely recognised as one of the most important factors influencing the attractiveness of public transport and, consequently, travellers' mode choice [1–4]. It refers to how often a public transport service operates within a given period [1]. Service frequency is also recognised as an important quality attribute in regional bus transport, while empirical evidence from low-density regions indicates that low bus frequencies can negatively affect public transport use [5,6]. In this study, regional public transport refers to public transport services connecting separate urban areas or urban and rural areas, with most trips

undertaken on a regular basis, generally ranging from daily to weekly travel [5]. Public transport use is quantified using passenger trip rates, expressed as the daily number of passenger trips per resident of the respective locality [7]. Separate measures are considered for adults and for children and young people. In regional bus transport, however, transport demand is generally lower than in urban areas, settlement patterns are more dispersed, and transport networks are less dense [8–11]. Under such conditions, service frequency is more appropriately expressed as the number of daily bus service pairs provided on a route or according to the origin–destination relation, rather than as departures per hour or headway between consecutive services [12]. In practice, this measure reflects the level of service available to passengers and the extent to which it enables residents to undertake everyday trips related to work, education, healthcare, and access to public and commercial services.

Despite the widely recognised importance of service frequency in determining public transport use [13], relatively few studies have attempted to identify specific service frequency thresholds corresponding to different levels of service. Consequently, decisions regarding the design of public transport services are often based on practical experience, financial constraints, or local conditions, rather than on empirical evidence indicating how many daily bus service pairs are required to ensure a minimum acceptable level of service, obtain an optimal level of provision, or identify the point at which further increases in service frequency yield only marginal benefits.

This issue is particularly important in rural and non-urban areas, where public transport performs an essential social function by reducing transport exclusion and providing access to essential public services. At the same time, the limited financial resources available for the provision of public transport services require transport authorities to define service standards in a rational and evidence-based manner.

From the perspective of sustainable mobility, regional bus transport planning should take into account both social and economic considerations. On the one hand, the level of service should provide adequate access to employment, education, healthcare, shopping, and leisure opportunities for residents of dispersed settlements and for people with limited access to private transport. On the other hand, excessive expansion of service provision may require substantial financial resources while generating progressively smaller increases in passenger ridership. A sustainable approach to regional transport planning therefore constitutes a multi-criteria decision-making problem that requires balancing conflicting objectives—specifically, guaranteeing adequate public access to transport services while ensuring the efficient and rational allocation of public funds [14–16].

The aim of this study is to identify the relationship between the number of daily bus service pairs and passenger trip rates in regional public transport, in addition to determining characteristic service levels that can support evidence-based and sustainable regional bus service planning. The analysis was conducted separately for adults and for children and young people in order to examine how service frequency affects public transport use in different passenger groups.

An additional objective of this study is to compare the relationships observed in Poland and the Czech Republic. The Polish analysis is based on field surveys conducted on 29 regional bus routes located across ten regions of the country, whereas the Czech case is represented by two regions with well-developed public transport systems—the Plzeň Region and the Vysočina Region. This comparative approach makes it possible to examine the performance of regional bus transport systems operating under different institutional and organisational conditions.

The comparison is also relevant because regional public transport in Poland and the Czech Republic has developed under substantially different institutional and organisational conditions. In Poland, the transformation of the former nationwide PKS (Państwowa

Komunikacja Samochodowa: State Road Transport) system resulted in a fragmented regional bus market, with most regional services operating on a commercial basis, while public financing was limited to statutory fare discounts [17]. In the Czech Republic, the former ČSAD (Československá Státní Automobilová Doprava: Czechoslovak State Motor Transport) system similarly underwent restructuring and fragmentation during the post-socialist transformation. However, the subsequent establishment of regional governments in 2001 led to a stronger public role in the organisation and financing of regional public transport. Regional authorities assumed responsibility for regional bus and rail services and increasingly organised their provision through public service contracts and regional transport organisations, contributing to the development of integrated public transport systems [18,19].

Comparing the results also makes it possible to assess whether the relationship between service frequency and public transport use is consistent across the national and regional contexts represented by the two countries considered in this study. Furthermore, it enables an assessment of whether differences in public transport use associated with service frequency may also reflect broader organisational and functional characteristics of the transport systems analysed. Consequently, this study not only identifies characteristic service levels but also examines the comparability of the identified patterns under different operating conditions of regional public transport systems.

Although the spatial scales of the analysed datasets are not identical, the comparison does not treat Poland and the two Czech regions as equivalent administrative units. Instead, the same analytical procedure is applied to a common unit of analysis: the origin–destination relation between a locality and its regional centre. These relation-level data are subsequently aggregated to construct ARTR_agg (Adult Regional Public Transport Trip Rate) and YRTR_agg (Youth Regional Public Transport Trip Rate) and to examine their relationship with service frequency within each study area. The resulting relationships are then compared across the three areas, and characteristic frequency thresholds are derived using the same modelling approach. The selected Czech regions provide detailed data and represent well-developed regional public transport systems that allow the same analytical approach to be applied as in the Polish case. Thus, the comparison concerns the empirical relationship between service frequency and public transport use under different national and regional contexts rather than a direct comparison of national and regional administrative aggregates. The difference in spatial scale is nevertheless acknowledged as a limitation when interpreting the transferability of the results.

The remainder of this study is structured as follows: Section 2 reviews the relevant literature on determinants of public transport attractiveness and identifies key research gaps. Section 3 presents the methodological framework, while Section 4 describes the research dataset from Poland and the Czech Republic, the model fitting, and the resulting service standards. Section 5 discusses the empirical findings and their implications for sustainable mobility planning. Finally, Section 6 provides concluding remarks, discusses study limitations, and outlines directions for future research.

2. Literature Review

Service frequency is widely recognised as one of the most important determinants of public transport attractiveness and use [13,20,21]. In regional public transport, Hansson et al. [5], based on a review of 37 studies, identified service frequency as one of the most frequently reported service attributes influencing passenger preferences, alongside reliability, travel time, comfort, and network coverage. At the same time, these authors noted that regional public transport has received considerably less research attention than urban systems and that the operational aspects of service frequency, such as timetable

planning and service levels, remain insufficiently investigated. Rasca and Saeed [6] confirmed the importance of frequency in regional transport systems serving small towns and rural settlements, identifying it as one of the strongest factors affecting public transport use alongside travel time, fares, parking availability, motorisation, and walking distance to stops. These findings are particularly relevant to regional bus transport, where dispersed settlement patterns and lower demand create different planning conditions from those found in large urban systems [22].

Empirical research has consistently demonstrated a positive relationship between service provision and public transport demand. Paulley et al. [23], synthesising evidence from numerous studies, estimated the short-run elasticity of bus demand with respect to service supply to be approximately 0.38 and the long-run elasticity to be around 0.66. They also showed that passenger responses vary according to the existing level of service, with stronger effects observed where initial service provision is low, particularly in rural areas. Berrebi et al. [24], using multi-year Automatic Passenger Count data and fixed-effects panel models for four major US bus networks, similarly found that increases in service frequency consistently lead to higher ridership. Their results further demonstrated that the marginal effect of additional services decreases as the initial level of frequency increases. Chiou et al. [25], using observed public transport use across 348 administrative units, also identified the frequency of intercity bus services as an important factor influencing public transport utilisation while emphasising that its effect varies across spatial contexts. Taken together, these studies confirm that frequency is an effective instrument for increasing public transport use, but its impact depends on the existing service level and the characteristics of the transport system.

A related research stream addresses the question of how service frequency should be designed rather than simply whether it affects demand. Furth and Wilson [15] proposed a frequency optimisation framework in which passenger benefits and operator costs are considered simultaneously, a problem later comprehensively reviewed in the context of transit network planning by Schöbel [26], demonstrating that frequency should represent a balance between improved service quality and the resources required to provide additional services. Ruiz et al. [16] similarly treated frequency as an important planning instrument and showed that adjustments in service levels can improve accessibility and spatial equity without requiring major infrastructure changes. In this vein, Żochowska et al. [27] emphasised that discrepancies between departure frequencies (service headways) and spatiotemporal travel demand frequently result in significant variations in public transport accessibility. This underlines the importance of evaluating service supply in relation to demographic and territorial realities. These studies indicate that the objective of service planning should not be to maximise the number of departures but rather to determine a level of service that provides an appropriate balance between passenger benefits and operating resources [28,29]. The costs of organising regular public transport services are particularly relevant in less urbanised areas, where lower and more dispersed demand may make conventional fixed-route services relatively resource-intensive. For this reason, Demand Responsive Transport (DRT) is increasingly considered an alternative to traditional regional bus services operating according to fixed timetables and predetermined stops [30]. In DRT systems, routes, departure times, and stops—often virtual—can be adjusted to current demand, typically through mobile applications or dispatchers [31].

Nielsen and Lange [32] extended this perspective by proposing a qualitative classification of service levels based on frequency, including “forget the timetable”, “fixed-minute timetable”, and “service on demand”. They argued that frequency should be designed in relation to the desired quality of service and that the relationship between frequency and public transport use is subject to diminishing returns. Their proposed service levels,

however, were conceptual rather than empirically derived. Thus, although the literature provides approaches for optimising frequency and conceptual frameworks for defining service levels, it offers considerably less evidence on the empirical identification of specific frequency thresholds corresponding to different levels of public transport attractiveness.

The existence of diminishing returns is particularly relevant when considering the saturation effects of increasing service frequency. The evidence reviewed by Paulley et al. [23] and the empirical results of Berrebi et al. [24] indicate that the strongest ridership response generally occurs at relatively low levels of service, and successive frequency increases generate progressively smaller increases in demand. This implies a non-linear relationship between frequency and public transport use. However, most existing studies quantify this relationship using demand elasticities or estimate the effects of changes in service provision, rather than identifying characteristic points at which particular service levels are reached or when the benefits of further frequency increases become limited.

Despite substantial progress in understanding the role of service frequency, empirical evidence linking specific frequency levels to different levels of public transport attractiveness remains limited. In particular, relatively little is known about the frequency thresholds associated with minimum and higher levels of service and about the point beyond which further increases in frequency result in only limited additional benefits.

This gap is particularly evident in regional bus transport. Most previous studies have focused on urban systems, using data from individual routes or entire networks, while considerably less attention has been devoted to regional areas characterised by dispersed settlement patterns, lower demand, and different organisational conditions. Moreover, the literature provides few empirically based operational standards specifying the number of services that could support regional bus service planning and quality assessment.

Addressing this gap constitutes the primary objective of the present study. Unlike previous research, which has largely concentrated on estimating demand elasticity or optimising service provision, this study employs logistic functions to model the relationship between bus service frequency and the utilisation of regional public transport. This approach makes it possible not only to describe the non-linear relationship between service frequency and public transport use but also to empirically identify characteristic frequency thresholds corresponding to minimum, basic, optimal, and high service levels. The level around the inflexion point is interpreted as an optimal service level, reflecting a stage at which further increases in frequency continue to increase public transport use but with progressively lower marginal effects. These thresholds provide the basis for a practical classification of regional bus service frequency standards.

Particularly relevant to the present study is the observation that the relationship between service frequency and public transport use may differ across passenger groups. The analysis therefore examines adults and children and young people separately, allowing the applicability of the identified frequency thresholds to be assessed for different groups of users.

3. Methodological Framework

The research procedure was structured into four main stages, as illustrated in the BPMN (Business Process Model and Notation) diagram presented in Figure 1. The research work assumed four main tasks:

- I—Initial steps;
- II—Data collection and preparation;
- III—Public transport use indicators and data aggregation;
- IV—Relationship modelling.

I—Initial steps: I.1 and I.2

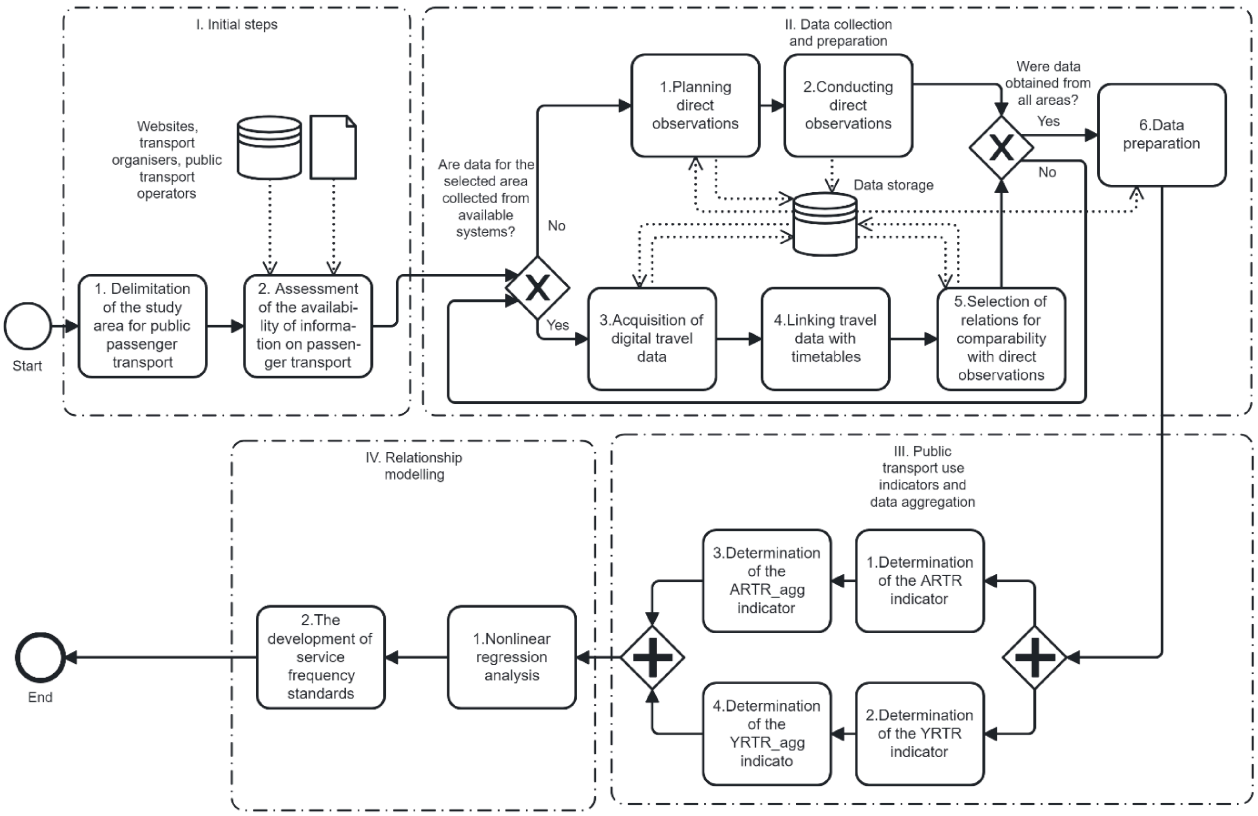


Figure 1. The research methodology concept.

This stage consists of two steps. The first step involves the selection of areas designated for this study (Step 1: Delimitation of the Study Area for Public Passenger Transport). The second step (Step 2: Assessment of the Availability of Information on Passenger Transport) focuses on identifying potential sources of information related to the provision of public passenger transport within the selected areas.

Our experience indicates that the availability of such data varies considerably depending on the study area, transport authority, and operator. Potential sources include websites, paper-based documentation, and digital data formats (e.g., GTFS, NeTEx, CSV), as well as ticket sales data.

II—Data collection and preparation: II.1 to II.6

At this stage, six steps are envisaged. Depending on the results obtained in Step I.2, it may be necessary to plan and conduct direct observations on selected routes. Steps 1 (planning direct observation) and 2 (conducting direct observations) are applied when passenger transport data are unavailable or when public transport vehicles are not equipped with passenger counting systems [12]. When direct observations are conducted, all services operating on the analysed routes during the observation period should be examined. The main potential sources of measurement error include the incorrect assignment of passengers to passenger groups, overlooking individual passengers, and day-to-day variation in passenger numbers. These sources of uncertainty should be considered when interpreting the resulting passenger volumes. Step 3 (acquisition of digital travel data) involves obtaining digital data from the systems of the operator, transport authority, or carrier. Where electronic ticketing or passenger registration systems are available, these data should be preferred to manual counts because they provide systematic records of passenger transactions. The completeness and consistency of the obtained records should nevertheless

be checked before further processing. Subsequently, sales data should be linked with timetables (Step 4, linking travel data with timetables) to obtain a comprehensive picture of the transport services offered for each transport relation. In the next step—Step 5 (selection of relations for comparability with direct observations)—those relations are selected from the entire dataset that allow comparable conditions to be achieved with the direct observation studies. This stage of the proposed method concludes with data preparation (Step 6), enabling the calculation of indicators and subsequent modelling. Records with missing or inconsistent information in variables required for the calculation of the main indicators should be excluded from the respective analysis rather than supplemented by arbitrary values. The objective is to achieve the highest feasible level of data completeness, consistency, and comparability while avoiding artificial modification of observed passenger volumes.

The proposed methodology may also be applied using alternative data sources where the preferred datasets are unavailable, provided that they allow for a sufficiently reliable estimation of travel demand and service supply.

III—Construction of public transport use indicators and data aggregation: III.1 to III.4

To quantify regional public transport use, two indicators were developed:

1. Step III.1: Adult Regional Public Transport Trip Rate (*ARTR*)—an indicator expressing the number of adult passengers travelling between locality k and the corresponding regional centre per inhabitant of that locality during the analysed period. In other words, *ARTR* represents the number of adult public transport trips generated per inhabitant. It is calculated as follows (1):

$$ARTR_k = \frac{\sum_{i=1}^{n}\left(AD_k^B + AD_k^A\right)}{POP_k}[-] \quad (1)$$

where:

- AD_k^B denotes the number of adult passengers travelling from locality k to the regional centre on bus service i [persons];
- AD_k^A denotes the number of adult passengers travelling from the regional centre to locality k on bus service i [persons];
- POP_k denotes the population of locality k [persons];
- n denotes the number of bus services connecting locality k with the regional centre during the analysed period.

2. Step III.2: Youth Regional Public Transport Trip Rate (*YRTR*)—an indicator expressing the number of school-age passengers travelling between locality k and the corresponding regional centre per inhabitant of that locality during the analysed period. In other words, *YRTR* represents the number of public transport trips made by children and young people per inhabitant. It is calculated as follows (2):

$$YRTR_k = \frac{\sum_{i=1}^{n}\left(YT_k^B + YT_k^A\right)}{POP_k}[-] \quad (2)$$

where:

- YT_k^B denotes the number of children and young people travelling from locality k to the regional centre on bus service i [persons];
- YT_k^A denotes the number of children and young people travelling from the regional centre to locality k on bus service i [persons].

The remaining notation is the same as that in Equation (1).

At the level of individual localities, the values of both indicators exhibit considerable variability resulting from the limited number of observations and the influence of incidental events. Consequently, the data show substantial dispersion, making it difficult to identify the underlying relationship between the level of public transport service and public transport use. To reduce the influence of random fluctuations, the data were aggregated into classes according to the number of daily bus service pairs. This approach makes it possible to reveal the underlying structural relationships, assess the effect of service frequency on public transport use, identify the potential saturation effect, and determine the functional form of the analysed relationship.

For each class of daily bus services, a population-weighted average of the *ARTR* indicator (step III.3) was calculated according to Equation (3):

$$ARTR_{agg,j} = \frac{\sum_{k=1}^{m_j} ARTR_k \cdot POP_k}{\sum_{k=1}^{m_j} POP_k} [-] \quad (3)$$

where:

- $ARTR_{agg,j}$ denotes the aggregated Adult Regional Public Transport Trip Rate for service frequency class j [−];
- m_j denotes the number of localities belonging to service frequency class j [−].

The remaining notation is the same as that in Equation (1).

The aggregated Youth Regional Public Transport Trip Rate YRTR_agg (step III.4) was defined analogously (4):

$$YRTR_{agg,j} = \frac{\sum_{k=1}^{m_j} YRTR_k \cdot POP_k}{\sum_{k=1}^{m_j} POP_k} [-] \quad (4)$$

where $YRTR_{agg,j}$ aggregated the Youth Regional Public Transport Trip Rate for service frequency class j [−]. The remaining notation is the same as that in Equations (1) and (3).

IV—Relationship modelling: IV.1 and IV.2

To determine the functional relationship between the level of public transport service, expressed as the number of daily bus service pairs (trips), and regional public transport use, non-linear regression analysis was performed using the aggregated indicators of adult public transport use ARTR_agg and youth public transport use YRTR_agg (step IV.1).

For each study region and indicator, four alternative regression models describing the relationship between service frequency and the indicator value were fitted: linear model, logarithmic model, power model, and logistic model.

The linear model assumes a constant increase in the indicator value with increasing service frequency. Under this assumption, each additional daily bus service pair generates the same increase in public transport use regardless of the existing level of service.

The logarithmic model describes a situation in which increases in service frequency lead to progressively smaller increases in the indicator value. The greatest gains are achieved at low service levels, whereas further increases in the number of daily bus service pairs result in diminishing improvements in public transport use.

The power model also accounts for diminishing marginal increases; however, unlike the logarithmic model, it preserves positive growth over the entire range of service frequencies analysed.

The logistic model additionally allows for the identification of the saturation effect. It assumes an initially rapid increase in the indicator value with increasing service frequency, followed by an inflexion point corresponding to the maximum productivity of service

provision, and finally a gradual approach to an asymptotic level beyond which further increases in the number of daily bus service pairs result in only marginal gains.

To ensure consistency with the underlying transport phenomenon, all analysed functions, except the linear model, were specified to take a value of zero when the number of daily bus service pairs equals zero. This assumption reflects the fact that, in the absence of bus services, public transport trips cannot be made and regional public transport use is therefore equal to zero.

The goodness of fit of the individual models was evaluated using the coefficient of determination (R^2). This statistic indicates the proportion of variability in the analysed indicator explained by the number of daily bus service pairs. A higher R^2 indicates a better fit of the model to the observed data.

For the linear model, the slope coefficient was interpreted as the average increase in the indicator associated with one additional daily bus service pair. For the logarithmic and power models, the estimated parameters were used to assess the rate of growth and the degree of diminishing marginal effects. For the logistic model, particular attention was paid to the asymptote (L), representing the asymptotic level of the fitted public transport use indicator; the growth rate parameter (l); and the inflexion point (x_0), representing the inflexion point of the fitted logistic function, where the marginal increase in the predicted indicator is maximal. The logistic relationship was specified in a constrained form, ensuring that the predicted value of the public transport use indicator equals zero when the number of daily bus service pairs is zero. The function was defined as follows (5):

$$y(x) = L\frac{\frac{1}{1+\exp[-l(x\ -x_0)]} - \frac{1}{1+\exp(lx_0)}}{1 - \frac{1}{1+\exp(lx_0)}}, \tag{5}$$

where L denotes the asymptotic value of the indicator, l is the growth rate parameter, and x_0 is the inflexion point of the logistic curve. The characteristic service frequency thresholds were then calculated from the fitted function as the values of x corresponding to specified proportions of the asymptotic value. Specifically, x_{25}, x_{50}, x_{75}, and x_{95} denote the service frequencies for which $y(x)$ reaches 25%, 50%, 75%, and 95% of L, respectively. These thresholds were obtained by solving $y(x_p) = pL$, where p denotes the respective proportion of the asymptotic value. Because the logistic function is constrained to equal zero at $x = 0$, the inflexion point x_0 does not correspond to 50% of the asymptotic value (x_{50}); therefore, x_{50} and x_0 represent different characteristics of the fitted curve.

The development of service frequency standards (step IV.2) requires the identification of service levels corresponding to different degrees of utilisation of the transport system's potential. In this study, an empirical approach was adopted based on the relationship between the number of daily bus service pairs and regional public transport use.

The subsequent analysis was based on the ARTR_agg indicator, describing adult public transport use. This indicator was selected because the relationship between service frequency and public transport use was considerably stronger for adults than for children and young people. Moreover, adults have a wider range of alternative travel options, such as private cars, bicycles, and shared mobility services, making their travel behaviour more sensitive to the level and quality of public transport provision.

The proposed service levels were derived from the characteristic points of the logistic function describing the relationship between service frequency and the ARTR_agg indicator. It was assumed that each service level corresponds to a specified proportion of the asymptotic value of the logistic function, interpreted as the maximum potential level of adult public transport use. Accordingly, the thresholds corresponding to 25%, 50%, 75%, and 95% of the asymptotic value, denoted as x_{25}, x_{50}, x_{75}, and x_{95}, respectively, were adopted.

These threshold values represent successive stages in the development of public transport services—from the minimum level required to ensure basic system functionality, through intermediate stages associated with increasing public transport use, to the saturation level, beyond which further increases in service frequency yield only marginal benefits. This approach makes it possible to relate service frequency standards directly to observed passenger behaviour rather than relying solely on expert judgement or conventional planning practice.

4. Implementation of the Research

4.1. Study Area

This study was conducted for three study areas comprising Poland (1) and two regions of the Czech Republic: the Plzeň Region (2) and the Vysočina Region (3). The selection of these study areas was intended to compare the relationship between the level of service and regional public transport use in transport systems characterised by different levels of development and organisational structures.

For Poland, the analysis was based on data collected from 29 regional bus routes located across ten regions of the country [12]. These routes represented independent and non-integrated transport systems operated either on a commercial basis or under contracts awarded by local public transport authorities. For the Czech Republic, this study included two regions with well-developed regional public transport systems operating under integrated fare and timetable systems.

The basic unit of analysis was the origin–destination relation between a locality and its regional centre, which performs administrative, educational, and service functions. Although Poland represents a national-level study area, whereas the Plzeň and Vysočina Regions represent regional-level areas, the comparison was conducted at the common locality–regional centre origin–destination level rather than at the level of administrative units. This common unit of analysis allows the relationship between service frequency and regional public transport use to be examined consistently across all three study areas.

4.2. Data Collection and Preparation

The analysis was based on data describing bus service frequency, the population of individual localities, and the number of passengers travelling between localities and their corresponding regional centres. The data were collected in the fourth quarter of 2023, with service frequency determined from timetable information.

In the case of Poland, due to the highly fragmented organisation of regional bus services and the limited availability of electronic passenger registration systems, it was necessary to collect data through direct onboard observations. During the surveys, all bus services operating on the analysed routes during the observation periods were examined, and passenger journeys between individual localities and nearest regional centres were recorded and classified into six groups: concessionary single-ticket passengers (including persons with disabilities and children under four years of age), adults travelling with single tickets, senior citizens travelling with single tickets, children and young people travelling with single tickets, adults travelling with season tickets, and children and young people travelling with season tickets. Due to the very small number of university students, this group of passengers was included in the adult passenger group. Although all services on the analysed relations were covered, a small degree of measurement uncertainty cannot be completely excluded.

The collected data were subsequently aggregated to the level of the origin–destination relation between each locality and its regional centre. For each analysed relation, a record was created containing information on the number of passengers by passenger group, the

number of bus services, the travel distance, ticket prices to the regional centre, and the socio-economic characteristics of the analysed localities.

This process resulted in 300 analytical records, each representing a locality–regional centre origin–destination relation and containing information on the total number of passenger trips between the two locations, the number of daily bus service pairs, ticket fare, travel distance and travel time, and other socio-economic characteristics of the areas surrounding the analysed localities.

For the Plzeň Region and Vysočina Region, passenger data were obtained from electronic ticketing systems operating on regional bus services and were collected during selected periods in the first half of 2024. These systems recorded both ticket sales and the mandatory registration of journeys made using season tickets and free-of-charge rides. This was possible due to the existence of a single regional public transport authority and the mandatory registration of all journeys made by public transport. The data distinguished the passenger groups (adults, senior citizens, university students, children, and young people), with separate information available for journeys made using both single and season tickets.

The Czech datasets consisted of individual ticket sales transactions and records of journeys made using season tickets and free travel passes. The original datasets covered several consecutive months of operation and contained more than 3.2 million records for the Plzeň Region and more than 1.5 million records for the Vysočina Region. To ensure comparability with the Polish data, the analysis was restricted to five consecutive workdays outside public holidays and school vacation periods. For each origin–destination relation, the final passenger volume used in the analysis was calculated as the average daily number of passengers over the five-day observation period.

Preparing the Czech datasets required a multi-stage process of data integration and processing. Ticketing data were linked with timetable information to identify the served localities, determine the transport supply, and derive travel characteristics. The datasets were then supplemented with statistical information on population and other socio-economic characteristics of the analysed localities.

To ensure the highest possible comparability between the Polish and Czech analyses, additional selection criteria were applied. Localities with direct railway connections to regional centres and those with alternative direct bus connections to other regional centres were excluded from further analysis. This allowed for a focus on origin–destination relations in which regional bus services are the main means of transport to the regional centre.

Finally, a unified database describing the relations between localities and regional centres was created for all analysed areas. For the Czech regions, the original ticketing data were aggregated to obtain the average daily number of passenger trips between each locality and its corresponding regional centre. These data were combined with information on ticket fares, travel distance and travel time, the number of daily bus service pairs, and other socio-economic characteristics of the analysed localities. This procedure resulted in 121 records for the Plzeň Region and 376 records for the Vysočina Region. The resulting database formed the basis for constructing the regional public transport use indicators and for subsequent statistical analyses.

To characterise the study areas and assess the comparability of the analysed datasets, descriptive statistics were calculated for the selected variables and are presented in Table 1. Particular attention was paid to demographic and settlement characteristics, the level of public transport service, and public transport use indicators, which provide the basis for subsequent analyses.

Table 1. Characteristics of analysed datasets (median values).

Variable	Poland (1)	Plzeň Region (2)	Vysočina Region (3)
Number of analysed relations [–]	300	121	376
Locality population [inhabitants]	257	245	193
Regional centre population [inhabitants]	16,995	12,510	15,577
Number of daily bus service pairs [–]	5.5	9.0	8.0
Distance to the regional centre [km]	15.8	14.1	13.9
Single fare to the regional centre [PLN] [1]	9.00	4.55 [2]	4.73 [2]
Adult passengers per 1000 inhabitants [persons/1000 pop]	6.23	49.80	31.41
Children and young people per 1000 inhabitants [persons/1000 pop]	21.98	19.61	25.53
Average gross monthly wage [PLN] [1]	5639	7617 [2]	7308 [2]
Motorisation rate [cars/1000 inhabitants]	776	676	570

[1] 1 EUR = 4.32 PLN; [2] converted from CZK to PLN: 1 PLN = 0.1749 CK.

Despite differences in the number of analysed relations between regions (1), (2), and (3), the datasets showed broadly comparable characteristics in terms of settlement structure and spatial conditions. The median population of the analysed localities was 257, 245, and 193 inhabitants, respectively, indicating the predominance of small settlements in all three datasets. Similarly, the median distance to the regional centre ranged from 13.9 to 15.8 km. These similarities provide a comparable spatial context for examining regional bus transport use, despite the different administrative scales of the study areas.

The most pronounced differences between the study areas concerned the level of public transport service. The median number of daily bus service pairs was 5.5 in Poland, 9.0 in the Plzeň Region, and 8.0 in the Vysočina Region, indicating that the average level of service in the Czech regions was substantially higher than in Poland. At the same time, single fares to the regional centre were approximately twice as low in the Czech Republic as in Poland.

Particularly large differences were observed in public transport use by adults. The median number of adult passengers per 1000 inhabitants was 6.23 in Poland, compared with 49.80 in the Plzeň Region and 31.41 in the Vysočina Region. This indicates that adult use of regional public transport was approximately eight times higher in the Plzeň Region and five times higher in the Vysočina Region than in Poland.

In contrast, considerably smaller differences were found for children and young people. The median number of passengers per 1000 inhabitants was 21.98 in Poland, 19.61 in the Plzeň Region, and 25.53 in the Vysočina Region, indicating broadly comparable levels of public transport use among younger passengers across all analysed areas.

Overall, the study areas differed substantially in their level of public transport provision and adult public transport use while showing broadly similar characteristics in terms of settlement size and comparable distances to regional centres. This combination of comparable spatial characteristics and different levels of service and public transport use provides an appropriate basis for examining whether the relationship between service frequency and public transport trip rates is consistent across different national and regional transport contexts. The comparison is therefore not intended to treat Poland and the two Czech regions as equivalent administrative units but to assess the same empirical relation-

ship using a common locality–regional centre origin–destination unit of analysis and a consistent analytical procedure.

4.3. Results: Public Transport Use by Adults and by Children and Young People

This section presents the results of the analyses examining the relationship between the level of public transport service, expressed as the number of daily bus service pairs, and regional public transport use. The analyses were conducted separately for adults and for children and young people using the aggregated indicators ARTR_agg and YRTR_agg, respectively.

In the first stage, the goodness of fit of the linear, logarithmic, power, and logistic models was compared to identify the function that best describes the relationship between service frequency and public transport use. The fitted relationships obtained for Poland, the Plzeň Region, and the Vysočina Region were then analysed, and the estimated model parameters were compared.

Particular attention was paid to identifying the saturation effect and assessing the similarities and differences between the analysed regions. The results provide the basis for establishing the characteristic levels of public transport service presented in the following section.

To determine the functional relationship between the level of public transport service and regional public transport use by adults, four regression models were fitted: linear, logarithmic, power, and logistic. A comparison of the coefficients of determination R^2 presented in Table 2 was used to identify the model that best describes the observed relationship and serves as the basis for the subsequent analysis of the model parameters.

Table 2. Comparison of model fit for the relationship between ARTR_agg and the number of daily bus service pairs.

Model	Region			Average R^2
	Poland (1)	Plzeň Region (2)	Vysočina Region (3)	
Logistic	**0.731** *	**0.605**	**0.746**	**0.694**
Power	0.663	0.485	0.659	0.602
Logarithmic	0.683	0.543	0.682	0.636
Linear	0.596	0.379	0.569	0.515

* Bold values indicate the highest R^2 values for each category.

Comparison of the model fit for the relationship between ARTR_agg and the number of daily bus service pairs indicated that the logistic model provided the best representation of the observed relationship. In all analysed regions, the coefficient of determination (R^2) obtained for the logistic model exceeded those of the linear, logarithmic, and power models. The best fit was achieved for the Vysočina Region (R^2 = 0.746), whereas the lowest was obtained for the Plzeň Region (R^2 = 0.605). The value obtained for Poland was intermediate between those observed for the two Czech regions. Moreover, the logistic model was the only model to achieve an R^2 value exceeding 0.70 for both Poland and the Vysočina Region, indicating its superior ability to capture the observed relationship.

These results provide the basis for a more detailed analysis of the logistic model parameters describing ATRT_agg, including the identification of characteristic service frequency thresholds, such as the minimum service level and the saturation threshold, and their subsequent comparison across the analysed regions.

Figure 2 illustrates the relationship between the number of daily bus service pairs and the value of ARTR_agg, together with the fitted logistic curves for Poland, the Plzeň

Region, and the Vysočina Region. The logistic model parameters presented in Table 3 reveal substantial differences between the analysed regions in terms of adult regional public transport use. The most pronounced differences concern the asymptote (L), which represents the maximum value of the ARTR_agg indicator that can be achieved under very high levels of service provision. The estimated asymptote was 0.0298 for Poland compared with 0.0717 for the Plzeň Region and 0.0754 for the Vysočina Region. These results indicate that the potential level of adult public transport use in the analysed Czech regions is more than twice that observed in Poland. This finding is consistent with the descriptive statistics presented earlier, which showed substantially higher numbers of adult public transport trips in the Czech regions.

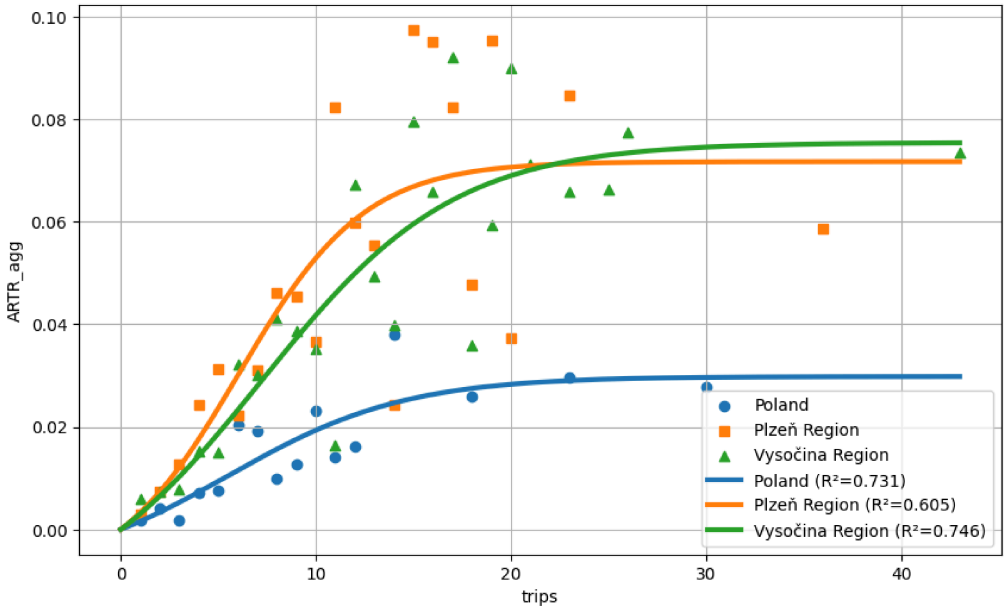


Figure 2. Relationship between ARTR_agg and number of daily bus service pairs with fitted logistic curves.

Table 3. Estimated parameters of the logistic model describing the relationship between ARTR_agg and the number of daily bus service pairs.

Region	Asymptote L	Growth Rate k	Inflexion Point x_0	Characteristic Service Levels				R^2
				x_{25}	x_{50}	x_{75}	x_{95}	
Poland (1)	0.0298	0.2201	5.50	4.08	7.63	12.01	20.12	0.731
Plzeň Region (2)	0.0717	0.3096	6.05	4.05	6.92	10.20	16.05	0.605
Vysočina Region (3)	0.0754	0.2028	7.21	5.03	9.09	13.96	22.81	0.746

Despite the differences in the coefficients of determination and the asymptotic values, the fitted logistic curves exhibit remarkably similar shapes across all three study areas. This similarity is particularly evident for the Plzeň and Vysočina Regions, where the curves have nearly identical forms and converge to comparable asymptotic levels. A similar pattern can also be observed for Poland. Although the asymptotic value is considerably lower, the overall shape of the logistic curve remains similar to those obtained for the Czech regions, particularly with respect to the location of the inflexion point and the thresholds corresponding to the initial growth phase and the saturation stage.

The values of the x_{25} threshold, corresponding to 25% of the asymptotic value, range from 4.05 to 5.03 daily bus service pairs. This indicates that, regardless of the region,

approximately four to five daily bus service pairs are required to achieve a basic level of adult public transport use.

Similar results were obtained for the inflexion point (x_0), which corresponds to the maximum productivity of service provision. The estimated values range from 5.50 to 7.21 daily bus service pairs, indicating a comparable level of service at which additional services generate the largest increase in adult public transport use.

The saturation threshold (x_{95}) also shows relatively little variation between the analysed regions, ranging from 16.05 to 22.81 daily bus service pairs. Beyond this level, further increases in service frequency result in only marginal increases in public transport use.

In addition to the x_{25}, x_0, and x_{95} thresholds, the intermediate values x_{50} and x_{75}, corresponding to 50% and 75% of the asymptotic value, respectively, were also determined. Across the analysed regions, these thresholds ranged from 6.92 to 9.09 daily bus service pairs for x_{50} and from 10.20 to 13.96 for x_{75}. The relatively narrow ranges indicate that intermediate levels of public transport use are reached at broadly comparable service frequencies across the analysed regions. Together with the similarity of the other characteristic thresholds, this finding supports the use of these thresholds as the basis for the multi-level classification of service frequency standards proposed in the following section.

It is noteworthy that the shapes of the fitted logistic curves are similar despite substantial differences in the overall level of public transport use between the analysed areas. As indicated by the descriptive statistics (Table 1), the study regions are characterised by similar locality sizes, comparable distances to regional centres, and broadly similar settlement structures. At the same time, adult public transport use was found to be several times higher in the Czech regions than in Poland. This indicates that the differences observed in the asymptotic values of the logistic functions cannot be explained solely by service frequency or the basic spatial characteristics of the analysed origin–destination relations. Instead, they may reflect the influence of additional factors related to the organisation of the public transport system, such as integrated fare systems, timetable coordination, service quality, passenger information, and long-term travel habits.

In the next stage of the analysis, the relationship between the number of daily bus service pairs and the YRTR_agg indicator, describing regional public transport use by children and young people, was investigated. As in the case of adults, the linear, logarithmic, power, and logistic models were compared to identify the function that best describes the observed relationship. Model performance was evaluated using the coefficient of determination (R^2), and the comparison of the results is presented in Table 4.

Table 4. Comparison of model fit for the relationship between YRTR_agg and the number of daily bus service pairs.

Model	Region			Average R^2
	Poland (1)	Plzeň Region (2)	Vysočina Region (3)	
Logistic	0.312	0.468	0.543	0.441
Power	**0.316** *	0.460	**0.556**	**0.444**
Logarithmic	0.306	**0.477**	0.528	0.437
Linear	0.267	0.418	0.523	0.403

* Bold values indicate the highest R^2 values for each category.

For the YRTR_agg indicator, the results are less conclusive than those obtained for adult public transport use. As shown in Table 4, none of the analysed models consistently provided the best fit across all study regions. For the logistic, logarithmic, and power models, the average R^2 values were between 0.437 and 0.444, and within each region,

differences were relatively small: 0.010 in Poland (where values were between 0.306 and 0.316), 0.017 in the Plzeň Region (values were between 0.460 and 0.477), and 0.028 in the Vysočina Region (values were between 0.528 and 0.556). This suggests a weaker and less well-defined relationship between service frequency and public transport use by children and young people.

In the Plzeň Region, the highest coefficient of determination was obtained for the logarithmic model (R^2 = 0.477), whereas the power model provided the best fit for Poland and the Vysočina Region (R^2 = 0.316 and R^2 = 0.556, respectively). At the same time, the differences between the power, logistic, and logarithmic models were minor, with the average R^2 values across all regions ranging from 0.437 to 0.444.

No single functional form provided a clearly superior fit across all three regions. Although the logarithmic model achieved the highest R^2 in the Plzeň Region (R^2 = 0.477), the power model provided the highest R^2 in Poland (R^2 = 0.316) and the Vysočina Region (R^2 = 0.556). Moreover, the power model achieved the highest average R^2 across the three regions (R^2 = 0.444), although its advantage over the logistic (R^2 = 0.441) and logarithmic (R^2 = 0.437) models was marginal. The power model was therefore retained as a common descriptive functional form for further analysis. This choice should not be interpreted as evidence that the power model provides a substantially better representation of the relationship. The relatively low R^2 values also indicate that this relationship between service frequency and public transport use by children and young people is considerably weaker than that observed for adults. The fitted power functions should therefore be regarded primarily as descriptive representations of the observed relationship rather than as strong predictive models. The relatively low R^2 values indicate that variations in YRTR_agg cannot be explained by service frequency alone and may also reflect differences in school-related travel patterns, timetable characteristics, and the spatial and demographic characteristics of the analysed localities.

Figure 3 illustrates the relationship between the number of daily bus service pairs and the YRTR_agg indicator, together with the fitted power functions for Poland, the Plzeň Region, and the Vysočina Region. Compared with the results obtained for the ARTR_agg indicator, these relationships exhibit greater scatter and lower coefficients of determination, indicating a weaker influence of service frequency on regional public transport use by children and young people.

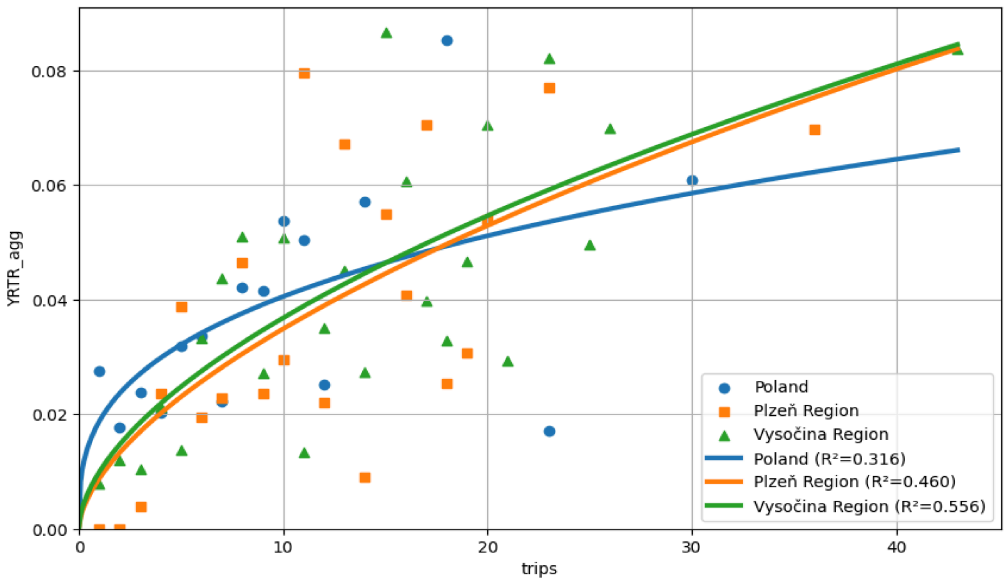


Figure 3. Relationship between YRTR_agg and number of daily bus service pairs with fitted power curves.

A positive relationship between service frequency and the YRTR_agg indicator was observed in all analysed regions. As the number of daily bus service pairs increases, public transport use by children and young people also increases. However, this relationship is noticeably weaker than that observed for adults, as reflected by both the lower coefficients of determination and the greater dispersion of observations around the fitted curves.

The parameters of the fitted power functions presented in Table 5 indicate a high degree of similarity between the two Czech regions. The estimated scale coefficients were 0.0088 for the Plzeň Region and 0.0099 for the Vysočina Region, while the corresponding exponents were 0.6004 and 0.5700, respectively. These results indicate that the estimated functional relationship between service frequency and YRTR_agg is broadly similar in the two Czech regions.

Table 5. Comparison of model fit for the relationship between YRTR_agg and the number of daily bus service pairs.

Region	Scale Coefficient (*a*)	Exponent (*b*)	R^2
Poland (1)	0.0187	0.3351	0.3164
Plzeň Region (2)	0.0088	0.6004	0.4600
Vysočina Region (3)	0.0099	0.5700	0.5562

Against this background, Poland exhibits a different relationship pattern. Despite the higher value of the scale coefficient (a = 0.0187), the lower estimated exponent (b = 0.3351) indicates a flatter increase in the fitted YRTR_agg values as service frequency increases. Consequently, at higher service levels, the predicted values of YRTR_agg in Poland remain below those observed for both the Plzeň and Vysočina Regions.

An interesting feature of the fitted power functions is the crossing of the Polish and Czech curves at approximately 15–16 daily bus service pairs. Below this service level, the model for Poland predicts slightly higher YRTR_agg indicator values than those for the Plzeň and Vysočina Regions. As service frequency increases, however, this relationship reverses, and the Czech curves indicate higher indicator values. This pattern results from the combination of a higher scale coefficient and a lower exponent for Poland, implying relatively higher public transport use at very low service levels but a weaker response to further increases in service frequency. In the Czech regions, the relationship is more dynamic; thus, additional bus services translate into a greater increase in the number of journeys made by children and young people.

In contrast to the results obtained for the ARTR_agg indicator, the differences between the analysed regions in public transport use by children and young people are considerably smaller. This is also confirmed by the descriptive statistics presented in Section 4.3, where the values of the *YRTR* indicator were similar across all study areas. These findings suggest that travel by children and young people is influenced to a greater extent by educational needs and regular journeys to school than by the overall attractiveness of the public transport offer. Consequently, although service frequency remains an important determinant of regional public transport use, its influence is less pronounced than in the case of travel by adults.

4.4. Service Frequency Standards for Regional Bus Transport

The analyses demonstrated that service frequency is an important determinant of regional public transport use, particularly among adult passengers. At the same time, the comparison of results obtained for Poland, the Plzeň Region, and the Vysočina Region showed that, despite substantial differences in the overall level of public transport use, the

characteristic parameters of the fitted logistic functions are remarkably similar across all analysed regions. This similarity applies both to the thresholds corresponding to the initial growth in public transport use and to the service levels associated with moderate, high, and near-maximum utilisation of the transport system.

These findings make it possible to translate the observed statistical relationships into a practical framework for planning regional bus service provision. Unlike many existing service frequency standards, which are largely based on expert judgement, the proposed approach is derived from an empirically established relationship between service frequency and actual public transport use.

Based on the estimated parameters of the logistic functions, the values of the x_{25}, x_{50}, x_{75}, and x_{95} thresholds were determined for all analysed regions. These thresholds correspond to the number of daily bus service pairs required to achieve 25%, 50%, 75%, and 95% of the maximum potential level of adult public transport use, respectively. The results are presented in Table 6.

Table 6. Characteristic service frequency thresholds corresponding to selected levels of ARTR_agg.

Region	Characteristic Service Levels			
	x_{25}	x_{50}	x_{75}	x_{95}
Poland (1)	4.08	7.63	12.01	20.12
Plzeň Region (2)	4.05	6.92	10.20	16.05
Vysočina Region (3)	5.03	9.09	13.96	22.81
Average	4.39	7.88	12.06	19.66

The results indicate relatively small differences in the threshold values across the analysed regions. The x_{25} threshold ranges from 4.05 to 5.03 daily bus service pairs, while the x_{50} threshold ranges from 6.92 to 9.09 daily bus service pairs. Achieving 75% of the asymptotic value of public transport use requires between 10.20 and 13.96 daily bus service pairs, whereas the near-saturation level (x_{95}) is reached at service frequencies ranging from 16.05 to 22.81 daily bus service pairs.

To obtain representative threshold values for the proposed service frequency standards, the threshold values were averaged across all analysed regions. The resulting values were 4.39, 7.88, 12.06, and 19.66 daily bus service pairs for the x_{25}, x_{50}, x_{75}, and x_{95} thresholds, respectively. After rounding, these correspond to 4, 8, 12, and 20 daily bus service pairs.

A sensitivity analysis was conducted to assess the robustness of the proposed reference values with respect to both the aggregation method and the composition of the analysed regions (Table 7). Using the median instead of the arithmetic mean resulted in the same rounded values for all four thresholds: 4, 8, 12, and 20 daily bus service pairs. The leave-one-region-out analysis showed some variation in the resulting reference values, with the largest variation observed for x_{95}.

Adopted reference values form a logical sequence of successive stages in the development of regional bus service provision. Increasing service frequency from approximately 4 to 8, then to 12, and finally to 20 daily bus service pairs corresponds to successive levels of public transport use. These results provide the basis for the proposed classification of service frequency standards presented in the following section.

Table 7. Sensitivity analysis of the proposed reference values across aggregation methods and regional sample compositions.

Threshold	Arithmetic Mean	Median	Leave-One-Region-Out	Adopted Reference Value
x_{25}	4.39	4.08	4.08–4.56	4
x_{50}	7.88	7.63	7.27–8.36	8
x_{75}	12.06	12.01	10.86–13.46	12
x_{95}	19.66	20.12	17.79–21.47	20

4.5. Proposed Classification of Service Frequency Standards

Based on the identified x_{25}, x_{50}, x_{75}, and x_{95} thresholds, a classification of service frequency standards for regional bus transport was developed. The proposed classification is based on the relationship between the number of daily bus service pairs and the degree of public transport use by adults, and it may serve as a practical tool for planning and evaluating regional bus services.

The proposed service levels represent successive stages in the development of public transport provision, ranging from the minimum level, at which regional public transport becomes practically useful for adults, to the saturation level, at which the transport system has almost reached its full potential.

The x_{25} threshold, corresponding to approximately four daily bus service pairs, can be interpreted as the minimum service level required to ensure basic accessibility for adult passengers. At lower service frequencies, public transport services are typically designed primarily to meet the needs of young passengers travelling to and from school. Although adults may still be able to make occasional journeys, the limited number and timing of services considerably restrict the use of public transport for everyday activities, such as commuting, shopping, accessing public services, or participating in social life. In practice, service levels of around three daily bus service pairs often require passengers to wait several hours for a return journey or to organise their daily activities around the timetable. Only when service frequency reaches approximately four to five daily bus service pairs does regional public transport become a realistic option for regular travel by adults. This level may therefore be regarded as the minimum service standard.

The range between the x_{25} and x_{50} thresholds, corresponding to approximately 4–8 daily bus service pairs, may be described as the basic service standard. At this level, the number of services is generally sufficient to support everyday travel related to work, education, and access to public services.

The range between the x_{50} and x_{75} thresholds, corresponding to approximately 9–12 daily bus service pairs, may be interpreted as the optimal service standard. At this stage, public transport becomes a realistic alternative to the private car for a substantial proportion of residents, while the availability of services provides considerable flexibility in travel planning. This range may be considered optimal because it represents a balance between transport benefits and the resources required to provide the service. This interpretation is supported by the shape of the logistic function: Although each additional daily bus service pair continues to generate an increase in passenger demand, the function has already passed its inflexion point ($x0$), indicating that the marginal effect of further frequency increases is gradually declining. Consequently, a service level of 9–12 daily bus service pairs may be regarded as the target standard for most regional bus corridors.

This conclusion is further supported by the results obtained for the Czech regions. The average number of daily bus service pairs was found to be 10.74 in the Plzeň Region and 9.68 in the Vysočina Region, corresponding closely to the proposed optimal

service standard. At the same time, both regions exhibited substantially higher levels of adult public transport use than Poland, suggesting that a service level of approximately 9–12 daily bus service pairs may represent an effective benchmark for planning regional bus services.

The next range, corresponding to the interval between the x_{75} and x_{95} thresholds (approximately 13–20 daily bus service pairs), represents the advanced service standard. At this level, public transport provides a high degree of travel flexibility and enables journeys to be undertaken conveniently throughout the day.

Beyond the x_{95} threshold, corresponding to approximately 20 daily bus service pairs, the transport system enters the saturation stage. Although further increases in service frequency may still generate additional passenger demand, the marginal gains become relatively small compared with the additional level of service provided. Consequently, the economic efficiency of further increasing service frequency gradually declines. A summary of the proposed service frequency standards is presented in Table 8.

Table 8. Proposed classification of service frequency standards for regional bus transport.

Level	Service Standard	Daily Bus Service Pairs [–]	Utilisation of Transport Potential [%]	Characteristics
0	Social service level	≤3	<25	Services primarily designed to meet school travel needs; limited opportunities for travel by adults.
I	Basic	4–8	25–50	Provides basic accessibility for adults, enabling regular trips to work, public services, and shopping.
II	Optimal	9–12	50–75	Public transport becomes a realistic alternative to private cars for a substantial proportion of residents.
III	Advanced	13–20	75–95	High service availability and considerable flexibility in travel throughout the day.
IV	High (saturation)	≥21	>95	Further increases in service frequency result in relatively small gains in public transport use.

The proposed classification combines ease of interpretation with a close correspondence to the statistical results. After rounding the average threshold values obtained for Poland, the Plzeň Region, and the Vysočina Region, the successive service standards correspond to approximately 4, 8, 12, and 20 daily bus service pairs. Consequently, moving from one service standard to the next reflects successive stages in the utilisation of the public transport system by residents.

It should be emphasised that the proposed classification should not be regarded as a rigid set of requirements applicable to all transport services. The number of daily service pairs should be understood as a general measure of the level of service, while the actual usefulness of a given service level depends, to a considerable extent, on how these services are distributed throughout the day. In particular, the departure times and the regularity of the timetable may substantially affect the ability of passengers to use public transport for different travel purposes, even when the total number of daily service pairs is the same. In practice, the appropriate service level should also take into account factors such as locality size, settlement structure, distance to the regional centre, availability of alternative transport modes, local travel demand, and temporal distribution of travel demand. Nevertheless, the proposed thresholds may provide a useful reference for planning new services, evaluating

existing service provision, and developing regional service standards, while the detailed timetable should be adapted to the specific characteristics and travel needs of each corridor.

4.6. Limitations and Applicability of the Proposed Standards

The findings presented in this study represent an empirical attempt to define service frequency standards for regional bus transport. However, several limitations relating both to the geographical scope of this study and to the characteristics of the analysed data should be acknowledged.

First, the analysis was based on data from Poland and two regions of the Czech Republic: the Plzeň Region and the Vysočina Region. Although these study areas differ considerably in terms of public transport use and the organisation of their regional transport systems, they do not represent the full range of regional transport models found across Europe. In particular, the proposed standards may not be directly applicable to highly urbanised areas; sparsely populated regions; or countries with substantially different social, economic, and transport conditions.

Second, the analysis was limited to regional bus transport. Rail services, which play an important role in regional mobility in many areas, were not considered, although they may substantially influence both public transport use and the required frequency of bus services. Consequently, in regions where bus and rail services operate as complementary modes, the proposed standards should be applied with caution.

A further limitation is that the analysis focused exclusively on travel between localities and their nearest regional centres. Although such travel patterns represent the dominant flows in regional bus transport, this study does not address travel between smaller towns or interregional journeys. Therefore, the proposed threshold values should primarily be interpreted as applicable to services providing access to the principal administrative, educational, and service centres of a region.

Despite these limitations, the results demonstrate a remarkably high degree of consistency across the analysed regions. The characteristic service frequency thresholds corresponding to successive levels of public transport use were found to be very similar in Poland and both Czech regions, despite substantial differences in overall public transport use and in the organisation of their regional transport systems. This finding suggests that the identified service levels may have broader applicability and could serve as a useful reference for regional transport planning in other regions.

Nevertheless, further research is needed to verify the transferability of the proposed standards. Future studies should include a larger number of regions and countries representing different models of public transport organisation. In particular, it would be valuable to extend the analysis to regions with a high share of rail transport, metropolitan areas, and countries characterised by different levels of public transport development. Such research would make it possible to assess the extent to which the proposed service frequency standards are universal and identify the circumstances under which they should be adapted to local conditions.

5. Discussion

The results confirm that service frequency is an important factor associated with regional bus use, but the relationship is clearly non-linear, with the largest increases occurring at lower service levels and progressively smaller effects as frequency increases. This finding is consistent with Berrebi et al. [24], who identified diminishing marginal effects of additional services. The main added value of the present study is that this non-linear relationship is translated into specific empirical frequency thresholds corresponding to successive levels of regional public transport use. In contrast to studies focusing primar-

ily on frequency elasticities or general service effects, the proposed approach identifies concrete reference levels that can be used in the planning and evaluation of regional bus services. Previous studies have also highlighted the importance of frequency for public transport attractiveness and use [1,2], including in regional systems serving small towns and dispersed settlements [5,6].

The observed relationship should not, however, be interpreted as evidence of a one-way causal effect of service frequency on public transport use. In regional transport systems, the relationship may be bidirectional: Higher service frequency can improve service attractiveness and stimulate demand, while existing or expected demand may also influence the level of service provided by operators or transport authorities. The cross-sectional nature of the analysed data does not allow these two mechanisms to be separated or the causal direction to be established. The identified frequency thresholds should therefore be interpreted as empirical service-use relationships rather than as estimates of the causal effect of increasing frequency.

An important finding is that the relationship between frequency and public transport use differs between passenger groups. The functions for adults and young people show distinct patterns, indicating that the strength and form of the observed relationship may vary with user characteristics and travel purposes. For children and young people, the relationship was weaker and less clearly defined, as reflected in the relatively low and similar R^2 values obtained for the alternative models. This complements the findings of Chiou et al. [25], who demonstrated a positive effect of frequency on public transport use without distinguishing between passenger groups, and Currie and Loader [29], who highlighted the complexity of the relationship between service improvements and travel behaviour. From a planning perspective, these findings suggest that frequency standards should not necessarily be applied uniformly across different passenger groups.

The present study provides an empirical extension of the service-level concept proposed by Nielsen and Lange [32]. While their framework defines frequency-based service levels conceptually, the present study complements this approach by identifying empirical frequency thresholds and relating them directly to successive levels of regional bus use. This provides a quantitative basis for distinguishing service levels and offers a more operational framework for evaluating existing provision and planning regional bus services.

The results provide a practical basis for differentiating service frequency standards in regional bus transport. The range of approximately 9–12 daily bus service pairs, identified around the intermediate thresholds of the logistic function, may be interpreted as a potentially optimal service standard: At this level, public transport becomes a realistic alternative to private transport, while further increases in frequency still produce benefits but with progressively smaller marginal effects. This interpretation is consistent with the planning perspective proposed by Furth and Wilson [15], Ruiz et al. [16], and Huang et al. [30], who emphasised the need to balance passenger benefits with the resources required to provide the service. In this sense, the proposed frequency classification can be viewed as a sustainability-oriented planning tool, as it links the social objective of maintaining adequate accessibility with the economic objective of avoiding disproportionate use of public resources. Importantly, this interpretation refers to the position of the service range within the logistic relationship rather than to a formal cost-based optimisation.

From a practical planning perspective, the proposed thresholds should be treated as differentiated reference levels rather than as a single minimum frequency requirement. The results suggest that service provision below approximately four daily bus service pairs may offer limited opportunities for regular adult travel, whereas increasing frequencies through the intermediate range of approximately 4–12 pairs are associated with successive increases in the level of public transport use represented by the fitted relationship. Above approx-

imately 12 pairs, further increases remain relevant but are associated with progressively smaller increments, with the x_{95} threshold reached at approximately 20 pairs. We therefore recommend using the proposed values as a screening and benchmarking framework when evaluating existing services or considering new regional bus connections. The final service decision should, however, be adjusted to local demand, settlement structure, alternative transport modes, and the distribution of departures throughout the day.

The present study also extends our previous research on regional bus service frequency standards [33], which used ROC analysis and the Kruskal–Wallis test to identify discrete frequency thresholds. The present study went further by modelling the continuous non-linear relationship between frequency and public transport use, allowing for the identification of the inflexion point and the saturation range in addition to the minimum service level. This provides a more continuous and behaviour-based framework for interpreting service frequency standards.

The results suggest that public transport usage does not increase linearly with service frequency and that certain frequency thresholds may be particularly important for achieving a significant increase in passenger numbers. From a planning perspective, this finding supports the use of frequency-based service standards when designing regional public transport systems. At the same time, the results suggest that increasing service frequency beyond a certain level (reaching demand saturation) may lead to diminishing returns.

6. Conclusions

The results demonstrate that the relationship between regional bus service frequency and public transport use is clearly non-linear and can be effectively described using a constrained logistic function. Across the three regions, the x_{25}, x_{50}, x_{75}, and x_{95} thresholds ranged from 4.05 to 5.03, 6.92 to 9.09, 10.20 to 13.96, and 16.05 to 22.81 daily bus service pairs, respectively. For adult passengers, aggregation of the regional thresholds yielded reference values of approximately 4, 8, 12, and 20 daily bus service pairs, corresponding to successive levels of service attractiveness. The range of approximately 9–12 daily bus service pairs, located around the intermediate thresholds and the inflexion point of the logistic function, may be regarded as a potentially optimal service standard, while further increases beyond approximately 20 pairs correspond to the near-saturation range and produce only limited additional benefits.

Despite substantial differences in the overall level of public transport use by adult passengers between Poland and the analysed Czech regions (the median number of adult passengers per 1000 inhabitants was approximately 5–8 times higher in the Czech regions than in Poland), the identified frequency thresholds were remarkably similar. This finding suggests that the relationship observed in the analysed regions may be relatively consistent across different national and regional contexts, although further research is required to determine the extent to which these thresholds can be transferred to other regions.

The relationship also differed between passenger groups. For adults, characteristic thresholds were identifiable, and the logistic functions provided relatively strong fits, with R^2 values of 0.731 in Poland, 0.605 in the Plzeň Region, and 0.746 in the Vysočina Region. The fitted function for Poland was consistently below those for the Czech regions, with an asymptotic level approximately 2.4–2.5 times lower. In contrast, for children and young people, the relationship was weaker, and no distinct frequency thresholds could be identified. The power model yielded R^2 values of 0.316 in Poland, 0.460 in the Plzeň Region, and 0.556 in the Vysočina Region, indicating substantially lower explanatory power than for adults. The fitted power curves for the two Czech regions were very similar, while the Polish curve crossed the Czech curves at approximately 15–16 daily bus service pairs, indicating different relationships between service frequency and YRTR_agg despite broadly

similar overall levels of younger passenger use. This indicates that service frequency provides a relatively strong explanation of the observed variation in adult public transport use, as reflected in the comparatively high R^2 values, while other factors may play a complementary role. For children and young people, the substantially lower R^2 values indicate that variations in service frequency explain a smaller proportion of the observed variation in public transport use. This may partly reflect the specific nature of school-related travel: Timetables are often adapted to school hours, while younger passengers have fewer alternative travel options than adults and may be more willing to wait for another connection when the timetable does not fully match their school schedule. For adults, by contrast, an inconvenient timetable may more readily result in a shift to private car travel.

The main contribution of this study is the empirical translation of the relationship between service frequency and observed regional public transport use into practical service frequency standards. The proposed classification can support the planning and evaluation of regional bus services by providing evidence-based reference levels for assessing existing provision and designing new services. The proposed standards should nevertheless be treated as reference values rather than rigid requirements, as their practical application should consider local demand, settlement structure, alternative transport modes, and the temporal distribution of departures. From the perspective of sustainable transport, they can support a balance between adequate accessibility and the efficient use of public resources, contributing to the social and economic dimensions of sustainable mobility. Environmental effects such as changes in emissions or modal shift were not directly assessed and require further research.

The identified thresholds should be interpreted as empirical associations between service frequency and observed public transport use, rather than as estimates of the causal effect of increasing frequency. Future research should test the proposed reference levels using data from additional regions and countries and examine their applicability in metropolitan and multimodal transport systems, particularly those with a greater emphasis on rail services.

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Abbreviations

The following abbreviations are used in this manuscript:

ARTR	Adult Regional Public Transport Trip Rate
BPMN	Business Process Model and Notation
YRTR	Youth Regional Public Transport Trip Rate

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