# Weekly Rhythms of Population Presence in the Bratislava Metropolitan Region: A Typology Based on Mobile Phone Data

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This paper aims to analyse the spatiotemporal rhythms of population presence in the suburban and rural hinterland of the Bratislava metropolitan region, with a particular focus on weekly patterns and their spatial differentiation. Using fuzzy time-series clustering, recurring temporal regimes across municipalities are identified and interpreted through the lens of rhythmanalysis, functional land-use patterns, and settlement hierarchy. The resulting categories, conceptualised as chronopolis, reflect distinct spatiotemporal logics – ranging from employment centres and multifunctional subcentres to monofunctional commuter zones and recreational hinterlands. A key contribution is made through the integration of weekend dynamics and the identification of regimes characterised by a declining presence, even on weekends. These regimes challenge traditional assumptions of suburban stasis and suggest emerging tensions between rapid suburbanization and local (in)capacity to retain residents. The analysis also captures a specific "Friday effect" observed in several suburban municipalities, potentially linked to the spread of teleworking and flexible work arrangements. The findings are argued to contribute to a more nuanced understanding of post-socialist suburban transformation, temporal functionality of space, and the methodological potential of rhythm-based classifications in urban and regional research.

*Keywords:* spatiotemporal rhythms, mobile phone data, time-series clustering, chronopolis, suburbanization, Bratislava metropolitan region, Slovakia

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## Introduction

Global urban development today is largely shaped by the process of suburbanization (Keil, 2018). Although suburbanization takes on various forms of settlement, it most often results in monofunctional residential enclaves that function as "bedroom communities" – emptying out during the day and filling up in the evening (Novák, Sýkora, 2007; Nemeškal, Ouředníček, Pospíšilová, 2020, Nemeškal, Ouředníček, Pospíšilová, Frydrych, 2022; Šveda, Sládeková Madajová, Barlík, Križan, Šuška, 2020a). The daily rhythm of presence in these "satellite towns" is largely driven by the need to commute to the city for work and everyday needs. This is not a new phenomenon; it has been characteristic of suburbs formed through advancements in transport technologies and the growing residential demands of the middle class (Fishman, 1996; Stanilov, Sýkora, *Eds.*, 2014; Ouředníček, 2007; Temelová, Novák, Pospíšilová, Dvořáková, 2011; Šveda, Šuška, 2020).

Why, then, does it still make sense to study the daily rhythms in these residential zones? There are several motivations. In the Slovak context, suburbanization not only creates new residential developments on greenfield sites but also commonly expands the existing settlement structure, particularly in rural municipalities (Šveda, Pazúr, 2018; Šveda, Boris, 2020). This generates a heterogeneous environment composed of (agricultural) rural spaces and new (suburban) built-up areas. The coexistence of long-established residents and newcomers is a compelling research object, not only from a social perspective (Potočný, 2006; Puldová, Ouředníček, 2006; Galčanová, 2013; Šveda, 2016), but also from the standpoint of overlapping rhythms of different social groups sharing the same suburban space (Nemeškal et al., 2020; Meij, Haartsen, Meijering, 2021).

The city and its hinterland are increasingly interconnected through commuting flows, production chains, and information networks. Alongside residential suburbanization, urban peripheries are also shaped by various production, logistics, and administrative functions. These transform the formerly "monotonous" rhythms of rural communities (Novák, Sýkora, 2007; Mulíček, Osman, Seidenglanz, 2015). For instance, a newly established car manufacturing plant operating in three shifts may significantly alter daily presence patterns across an entire region.

Furthermore, the motivation to monitor daily rhythms in suburban zones stems from emerging phenomena that reshape long-term patterns of spatial-temporal behaviour – not only in suburbs. Working from home and flexible work schedules have the potential to reduce the dependence of suburban residents on daily commuting (Vilhelmson, Thulin, 2016; Stiles, Smart, 2021). To what extent such new work practices affect suburban rhythms and reduce their monofunctional character remains an open and relevant research question.

This paper aims to analyse the spatiotemporal rhythms of population presence in the suburban and rural hinterland of a metropolitan region, with a particular focus on weekly patterns and their spatial differentiation. By applying fuzzy time-series

clustering to mobile phone data, the study develops a typology of functional chronopolises – territorial clusters exhibiting similar fluctuations in population presence. Specifically, the paper seeks to:

- Identify and typologize dominant presence rhythms during weekdays and assess their spatial differentiation regarding distance from the urban core, population size, and local functional orientation;
- Compare and interpret weekend temporal regimes, with emphasis on the role of second-home usage, recreational mobility, and low-activity residential zones, thereby moving beyond purely weekday-centric suburban models;
- Evaluate the extent to which new work arrangements (e.g., telecommuting, flexible hours) influence suburban rhythms and reduce spatial dependency on the urban core.
- Demonstrate the analytical value of rhythm-based classification in revealing hidden functional structures, transitional zones, and non-traditional urban-suburban dynamics that are often overlooked in conventional typologies based on work and residential community patterns..

Conceptually, the paper draws on chronogeographic approaches, particularly the concepts of chronotope and chronopolis, which provide a lens to capture the spatial and temporal dimensions of everyday rhythms (Osman, Mulíček, 2017). Methodologically, the analysis applies tools from the growing field of time-series clustering, which enables the identification of distinct weekly presence profiles (Aghabozorgi, Shirkhorshidi, Wah, 2015).

The spatial scope of this study is the Bratislava metropolitan region, defined as the combined territory of the Bratislava and Trnava self-governing regions (Šveda, Sládeková Madajová, Barlík, Bago, 2020b). Although the metropolitan region extends beyond the state borders to Austria and Hungary, in this paper we focus exclusively on the Slovak territory, as we had access only to data from the Slovak mobile network. This definition exceeds the extent of the city's daily commuting region (Halás, Klapka, 2024), but it enables us to capture rhythms in a more functionally diverse environment and consider broader spatial dynamics. Additionally, including the "urban shadow" allows us to explore rhythms that arise from non-daily activities – such as weekend migrations to second homes. We assume that the Bratislava metropolitan region is broadly analogous to other medium-sized cities in Central and Western Europe in terms of its spatiotemporal signatures, particularly with respect to commuting patterns, suburbanization dynamics, and the functional differentiation of metropolitan areas.

## Capturing rhythms of population presence

The study of daily rhythms is grounded in the conceptual domains of time geography (Hägerstrand, 1970), rhythm analysis (Lefebvre, 2004), and chrono-geography (Osman, Mulíček, 2017). One of the key conceptual foundations of time-geographical thinking originates in the work of T. Hägerstrand (1970), who emphasised the analytical potential of jointly considering space and time to understand behavioural patterns. While his time-space path diagrams were often simplified to abstract visualisations, the implications of his approach deeply influenced urban research and planning. Building on this, Henri Lefebvre (2004) criticised static and mechanistic notions of space and time, proposing instead a rhythmanalytical perspective. According to Lefebvre, both space and time are socially produced, and their meanings are embedded in systems of power and everyday practices.

Lefebvre's rhythm analysis has inspired a rich body of urban research, including the work of Czech geographers R. Osman and O. Mulíček, who have significantly contributed to extending rhythmanalytical thinking into the domains of urban temporality, spatial practice, and mobility structures (Mulíček et al., 2015; Osman, Mulíček, 2017). Drawing upon the concept of the chronotope – originally developed by Mikhail Bakhtin (2002) in literary theory – they reconceptualise urban localities as spatio-temporal entities defined by overlapping and coexisting rhythms.

According to Osman and Mulíček (2017), the chronotope serves as a heuristic tool for interpreting the polyrhythmic nature of urban places, where spatial forms are intertwined with temporal structures. By employing the chronotope, the locality can be grasped not only in a spatial/graphical way as a delimited piece of space, but also in a spatio-temporal way (graphically and narratively) as a timed, rhythmized place (Osman, Mulíček, 2017: 48).

A crucial operational element of this concept is the presence, absence, or co-presence of temporary or permanent users. These patterns of use create what the authors describe as the "temporal architecture of place" (Osman, Mulíček, 2017: 48). This approach allows researchers to analytically delineate typological categories of a place based on temporal patterns of human activity and interaction. Despite the inherently idiosyncratic character of each chronotope, they can be classified based on their rhythmic profiles, particularly when such profiles are derived from fluctuations in population presence over time. In this context, chronotopes that share similar rhythmic patterns, despite being spatially disconnected, are understood collectively as forming a chronopolis – a higher-order category of rhythmically aligned places (Osman, Mulíček, 2017).

The notion of *polis* here is conceptualised as a territory characterised by internal coherence, governed by a shared set of rules, practices, or symbolic norms. Chronopolis, in this sense, is not a contiguous space but a functionally and temporally integrated field, where remote locations become rhythmically synchronised through common social, institutional, or infrastructural patterns (Osman, Mulíček, 2017).

From this perspective, a metropolitan region can be seen as a rhythmic ensemble of such chronotopes, integrated not only functionally but also temporally, forming a distributed yet cohesive urban system.

Rhythms of any scale are structured by what Lefebvre (2004) termed pacemakers – elements that impose order and repetition upon space. These include institutional routines (work hours, school schedules), infrastructural systems (transportation nodes), and cultural patterns (weekend leisure), as well as socio-economic constraints and planning legacies that shape recurring spatial behaviours, all of which constitute the temporal fabric of the city (Lískovec, Lichter, Mulíček, 2022; Šveda et al., 2020a). Through rhythmanalysis, it becomes possible to read urban space not only through its spatial morphology but also through its temporal orchestration.

## Typologies of daily rhythms

Identifying typical temporal profiles of population presence provides a valuable entry point into rhythm analytical inquiry. In general, three prototypical regimes are distinguished: the residential regime, following a U-shaped curve with low daytime presence and evening peaks; the working regime (A-shaped), marked by a midday peak in activity and decline outside working hours; and the balanced regime, which reflects areas with low net mobility or functional mixture. This typology has been widely discussed and empirically applied by scholars analysing retail zones, mixed-use districts, and housing estates (Mulíček, Osman, 2018; Šveda et al., 2020a, Nemeškal et al., 2020). Nevertheless, such static classifications are inherently limited in capturing the diversity of real-world temporalities. Especially in polycentric metropolitan regions, urban rhythms tend to be fragmented, overlapping, and reconfigured throughout the day. Recent research by Stražovec, Erlebach, and Halás (2025), which employs Principal Component Analysis, Factor Analysis, and Cluster Analysis on full-week population presence data, illustrates how multivariate methods can reveal complex weekday and weekend dynamics within a unified analytical framework. Building on this line of inquiry, the present study advances the methodological perspective by applying time-series clustering techniques to mobile phone data, which allow rhythmically coherent zones to be identified directly from temporal trajectories rather than from aggregated indicators (Zhang, Yang, Zhen, Lobsang, 2020; Güller, Varol, 2024).

### *Time-series clustering for population presence analysis*

A deeper understanding of population presence rhythms requires robust methodological approaches, among which time series clustering plays a key role. This class of methods is designed to group time-dependent data based on similarity in temporal patterns. In the context of spatial analysis, the goal is to identify locations

that exhibit comparable temporal trajectories – rhythms. Time-series clustering involves several challenges, including temporal alignment, scaling, seasonality effects, and noise reduction. The choice of a suitable method depends on the nature of the data (e.g., sequence length, time granularity, seasonality), interpretability requirements, and computational constraints. A comprehensive review of clustering methods for time series is provided by Aghabozorgi et al. (2015).

Two principal types of clustering methods can be distinguished (Sadahiro, Kobayashi, 2014). *Whole matching methods* assess similarity across entire sequences over the same time span, while *subsequence matching methods* classify time series data based on their partial similarities. Whole matching methods are computationally efficient and suitable for analysing globally synchronised data trends. However, they may fail to detect localised or temporally shifted phenomena. In contrast, subsequence-based approaches offer higher resilience to temporal misalignments and can reveal a wider range of partial similarities – particularly useful in unsynchronised contexts, such as when similar behavioural patterns (e.g., increases in air pollution or population density) occur in different cities at different times. The primary drawback of these methods is their higher computational costs and potential over-flexibility, which can compromise interpretability. In many cases, the same pattern occurring in different time intervals may represent entirely distinct processes – such as increased midday presence in a district driven by either employment or leisure activity. In such scenarios, whole-series comparison is more suitable.

A crucial determinant of clustering performance is the choice of similarity measure. The commonly used *Euclidean distance* is sensitive to temporal shifts and scaling, making it suitable only for rigidly structured, synchronised datasets (e.g., regular sensor readings). For less structured data – such as biosignals or human mobility patterns – more flexible approaches are needed. These include *Dynamic Time Warping* (DTW), which enables temporal deformation to align similar shapes that occur at different times. While DTW improves matching under temporal misalignment, it is computationally intensive and prone to noise sensitivity (Wang, Mueen, Ding, Trajcevski, Scheuermann, Keogh, 2013). *Shape-Based Distance* measures, on the other hand, focus on the overall shape of the series and are less sensitive to amplitude variation and temporal offset, offering a compromise between robustness and efficiency.

With the rise of big data and advances in computational capacity (e.g., cloud computing), the field of time-series clustering has evolved significantly (Aghabozorgi et al., 2015). Contemporary algorithms now accommodate high dimensionality, spatio-temporal interdependence, and missing values. Moreover, *fuzzy clustering* approaches have emerged, enabling time series to belong to multiple clusters with varying degrees of membership (Maharaj, D'Urso, 2019). This is particularly useful for analysing complex urban areas where overlapping rhythms coexist – for instance, in mixed-use zones that simultaneously exhibit residential and work-related activity patterns.

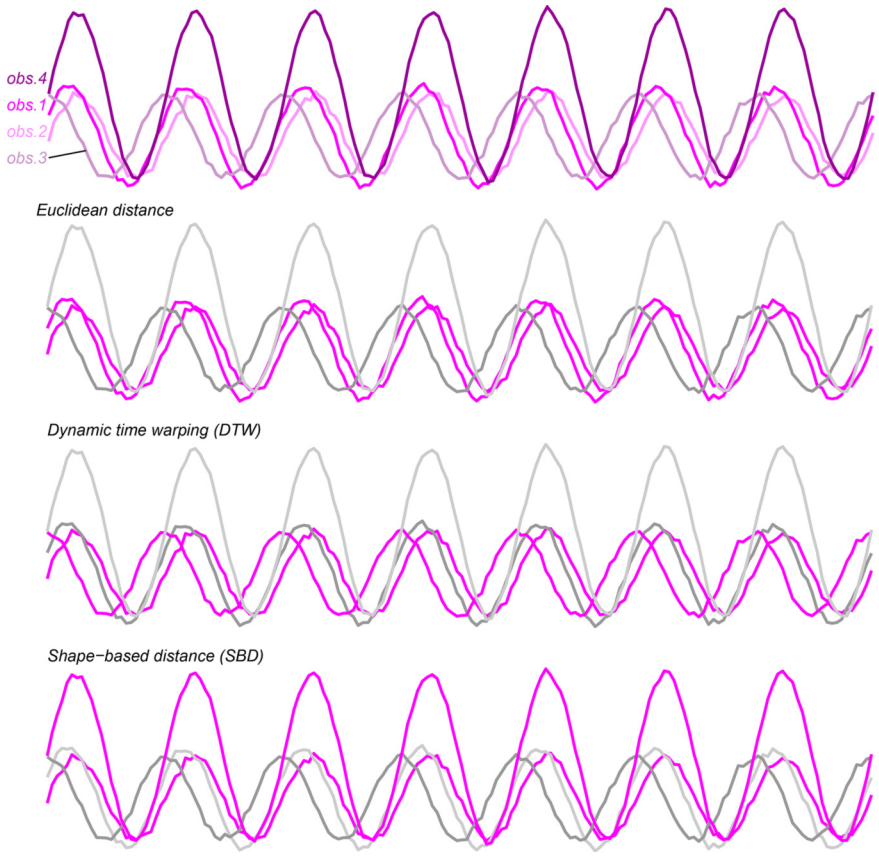


*Fig. 1: Clustering results of four time series using three distance measures: Euclidean distance, Dynamic Time Warping (DTW), and Shape-Based Distance (SBD). Series obs1 and obs2 have a similar pattern and amplitude; obs3 shares the same shape but is phase-shifted; obs4 has a similar shape but a higher amplitude. Each method groups the series differently based on its sensitivity to timing and scale.*

## Data and methods

The analysis of presence rhythms in over 300 municipalities and urban districts in the Bratislava metropolitan region, which has a population of approximately 1.3 million, is not feasible using conventional statistical data. Geolocation data from mobile networks have emerged as one of the most promising sources for capturing the spatial variability of population presence at a fine temporal resolution (Ahas, Aasa, Silm, Tiru, 2010; González, Hidalgo, Barabási, 2008; Järv, Ahas, Witlox, 2017). Despite their value, such data remain relatively uncommon, difficult to access, and methodologically challenging to process – justifying the need for a detailed discussion of the processing pipeline (Järv et al., 2017; Šveda, Hurbánek, Madajová, Rosina, Förstl, Záboj, Výbošťok, 2024).

### *Mobile network data preprocessing*

The fundamental spatial principle of mobile network geolocation data lies in the fact that a user's location is tied to their position within the mobile infrastructure – typically assigned to a specific network cell, defined either as a point or a polygon. In this study, each location is represented by a radiation polygon, which approximates the spatial coverage of a mobile signal. Each SIM card was assigned to the cell in which it recorded the highest number of activities within a given hour. This approach aims to approximate the most probable location of actual user activity; however, it is essential to recognise that this may still encompass incidental or transient positions (e.g., part of a movement chain during travel). Each SIM card was therefore counted only once per hour. The data used in this analysis were provided by Slovak Telekom and capture the space-time behaviour of approximately 365,000 mobile network users over a four-week period. Slovak Telekom is one of the largest mobile operators in Slovakia, with an estimated one-third market share, which underscores the representativeness of the analysed dataset.

For spatial analysis, mobile activity data must be meaningfully transformed into conventional territorial units – such as municipalities, districts, or grid cells. We employed a custom method (Šveda et al., 2024), based on the principle of dasymetric mapping, which enables a finer redistribution of mobile activity data within source zones using ancillary information. In our case, we used building volume data from the ZBGIS database (ÚGKK, 2017) as an ancillary layer.

Selecting an appropriate observation period to reflect regular daily population rhythms is a non-trivial task. It requires accounting for numerous factors such as public holidays, religious events, school breaks, university semester timing, and nationally significant occasions (e.g., elections, major cultural or sporting events). To eliminate random and seasonal fluctuations, we selected a four-week observation window, encompassing the winter period (16–22 January 2023), spring periods (6–12 March 2023 and 17–23 April 2023), and the early summer period (12–18 June 2023).

To enable the meaningful interpretation of daily presence patterns, adjusted for natural diurnal variations (e.g., nighttime SIM card reductions averaging 5.8% compared to daily peaks), we standardised the data using a two-step procedure. This includes both local and national-level adjustments, based on a reference time window. The formula is as follows:

$$P_{Sih} = (P_{ih}/P_{im}) / (\Sigma P_{ih} / \Sigma P_{im})$$

where $P_{ih}$ is the count of SIM cards in municipality $i$ at hour slot $h$, and $P_{im}$ is the mean count of SIM cards in municipality $i$ at 6 mid-weekday night hour slots (Tuesday, Wednesday, Thursday between 02:00 and 03:59).

### *Time-series clustering method*

To identify patterns in weekly time series of population presence, we applied fuzzy clustering using the *dtwclust* package in R (Sardá-Espinosa, 2019). This method extends the conventional *k-means* algorithm to temporal data, allowing each observation (i.e., municipality's weekly time series) to belong to multiple clusters with varying degrees of membership. This is especially suitable when dealing with spatial units of vastly different sizes and signal stability – such as small rural municipalities where mobile signal fluctuation, base station switching, and data sparsity may introduce additional temporal noise. Fuzzy clustering thus provides a more realistic depiction of "mixed profiles" (e.g., semi-rural/semi-urban settlements), which might otherwise be forced into a single rigid typology.

We set the number of clusters to $k = 5$, based on exploratory analysis, which showed that higher values did not yield additional interpretable patterns. The distance metric used was Euclidean distance, which computes similarity based on the direct point-wise difference between time series values. While more complex distance metrics (e.g., dynamic time warping) can capture temporal shifts, Euclidean distance is more appropriate when time series are already temporally aligned (e.g., hourly values over a standardised week).

As cluster centroids, we used the fuzzy c-means algorithm, which iteratively optimises the weighted average of time series profiles, using a fuzziness parameter $m = 2$. This parameter controls the degree of cluster overlap – higher values allow for greater shared membership across clusters. The resulting model returns not only the centroid profiles but also a membership matrix, which we further analysed to identify dominant and mixed-regime municipalities.

Given the nature of the dataset, a significant number of municipalities – especially those with fewer than 500 inhabitants – were associated with very low numbers of active mobile network users, in some cases as few as 100 SIM cards. This led to highly irregular and volatile time series, making it difficult to reliably assign such municipalities to one of the main clusters. To address this issue, we introduced an additional step: municipalities with a maximum cluster membership confidence below 0.5 were excluded from the five principal clusters and assigned to a separate ambivalent cluster. This threshold was selected based on a visual and statistical assessment of membership uncertainty and time series volatility. Importantly, the creation of this ambivalent category also aimed to account for specific rhythms that did not fit clearly into any of the dominant temporal patterns, thus preserving the analytical integrity of the overall typology.

A cluster analysis of hourly SIM card counts, reflecting fluctuations in the number of present mobile network users, was conducted across municipalities of the Bratislava metropolitan region during an average week. The analysis grouped municipalities into five distinct categories based on the temporal dynamics of user presence. In line with the conceptual framework of chronogeography, these recurring regimes can be interpreted as chronopolis – ensembles of chronotopes that, although spatially distant, exhibit analogous rhythmical profiles shaped by similar patterns of user presence.

The following section presents a brief overview of each identified chronopolis (Tab.1). The interpretation is based on comparative graphical analysis of aggregated daily (weekly) user presence profiles, computed for each chronopolis (Fig. 2). In addition to temporal patterns, the interpretation also considers the settlement structure and the functional orientation of municipalities (e.g., residential, employment, or mixed-use character). Particular attention is paid to identifying and understanding key pacemakers – elements such as institutional schedules, or socio-economic functions – that generate and stabilise the observed presence rhythms. The municipalities of the metropolitan area can be conceptualised here as a (large-scale) chronotope animated and "narrated" by a set of pacemakers and their rhythms.

*Table 1: Basic characteristics of identified chronopolises in the Bratislava metropolitan area*

| **Chronopolis** | **Number of municipalities** | **Number of inhabitants** | **Number of constructed dwellings (2003-2021)** |
|---|---|---|---|
| Chronopolis A: Workday regime of employment centres | 21 | 357 994 | 36 323 |
| Chronopolis B: Balanced regime of subcentres | 26 | 377 897 | 30 613 |
| Chronopolis C: Regime of bedroom suburbia | 113 | 287 744 | 41 573 |
| Chronopolis D: Weekend regeneration in natural settings | 41 | 38 856 | 4 025 |
| Chronopolis E: Commuting periphery | 121 | 195 364 | 20 019 |
| Ambivalent regime (not classified) | 17 | 50 296 | 7 569 |

*Chronopolis A: Workday regime of employment centres.* This chronopolis is characterised by a distinct "A-shaped" daily curve of mobile network activity during weekdays, with a rising number of SIM cards present in the morning hours, peaking around late morning, and subsequently declining in the afternoon. This temporal

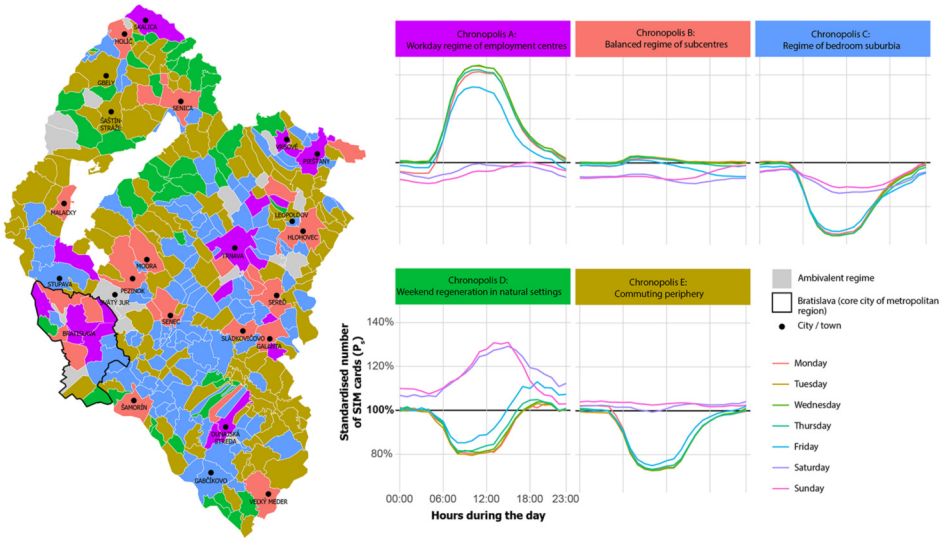


*Fig. 2. Classification of municipalities into chronopolises based on weekly presence patterns of mobile network users. The map displays the spatial distribution of chronopolises across the Bratislava metropolitan region, while the line charts show aggregated SIM card presence profiles representing the temporal rhythm in each cluster. Data source: Slovak Telekom, 2023.*

pattern is typical of municipalities that function as employment centres. The cluster includes key urban districts of Bratislava – Ružinov (Fig. 3a), Nové Mesto, Staré Mesto, Devínska Nová Ves and Vajnory – as well as major towns in the wider region such as Trnava, Skalica, Piešťany, and Dunajská Streda.

The number of active SIM cards begins to increase around 6:00 AM and reaches its peak approximately before noon. This can be interpreted as a reflection of the daily routines associated with primary and secondary schooling, where students typically return home around midday. Additionally, the weekday curves tend to be slightly asymmetric, extending further into the second half of the day. This asymmetry likely results from the structured timing of morning routines – driven by school and work commutes between 5:00 and 7:00 AM – contrasted with a more gradual and prolonged decline in activity between 2:00 PM and 8:00 PM.

Variations between individual weekdays are also observable, particularly on Fridays (Fig. 2), which tend to show a significantly lower daytime population peak. This trend may be attributed to the early onset of weekend activities, shorter office hours (e.g., in public administration), and the influence of student mobility patterns – especially among university students. Furthermore, the increasing prevalence of contemporary work arrangements, such as four-day work weeks, remote work, and flexible working hours, likely contributes to this shift.

While larger urban centres reflect a composite of overlapping daily rhythms shaped by multiple pacemakers (e.g., education, work, retail, services), the patterns

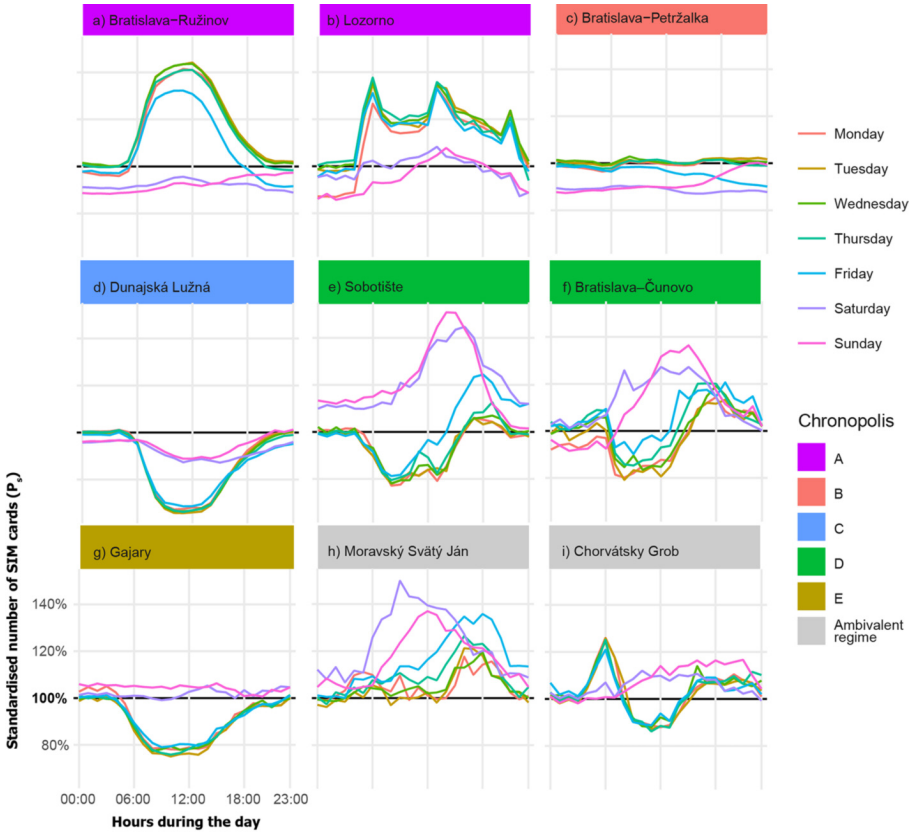


*Fig. 3: Daily regime of SIM cards presence in selected municipalities of Bratislava metropolitan region. Data source: Slovak Telekom, 2023*

observed in smaller municipalities are often more straightforward and tied to a dominant functional activity. Notably, this chronopolis also includes suburban or rural settlements such as Lozorno (Fig. 3b), Kostolné Kračany, and Voderady, where industrial production and logistics parks serve as the primary drivers of local daytime population regimes. In such contexts, the pronounced daily influx of mobile phone users indicates a clear employment-related rhythm.

*Chronopolis B: Balanced Regime of Subcentres.* This chronopolis comprises a relatively small cluster of municipalities, notably composed almost exclusively of towns – Šamorín, Malacky, Pezinok, Senec, Holíč, Hlohovec, and Sládkovičovo. These towns are characterised by a balanced regime in the presence of SIM cards throughout the day, indicating a relatively stable level of population presence between daytime and nighttime. This chronopolis stands out for not exhibiting the pronounced daytime depopulation typical of residential suburbs, nor the sharp inflows observed in dominant employment hubs.

A cautious interpretation of this balanced pattern suggests that the structure and quantity of local employment opportunities support a moderate level of daytime population retention. However, they are not sufficient to fully eliminate commuting flows, and thus a portion of residents likely travel to the regional core city or other employment centres. Crucially, this seemingly balanced daytime regime may in fact result from fundamentally different underlying conditions. On one hand, it may reflect low overall mobility, where both work and non-work activities are concentrated locally. On the other hand, it may stem from high mobility with roughly equal numbers of incoming and outgoing flows, resulting in a net-zero daytime population change.

A particularly noteworthy finding is the inclusion of Petržalka – Bratislava's largest residential district – within this chronopolis (Fig. 3c). Although it is not feasible to clearly disaggregate mobile network data at the intra-urban level, the balanced regime observed in Petržalka challenges its conventional classification as a monofunctional "bedroom community". Instead, it suggests that this large-scale housing estate supports a diverse mix of functions, offering residents opportunities for both employment and non-work activities throughout the day.

A similar pattern can be observed in other peripheral districts of Bratislava included in this cluster, such as Karlova Ves, Rača, and Záhorská Bystrica. These urban areas, though varied in their urban form and development history, exhibit a comparably balanced daily rhythm of mobile presence. In Karlova Ves and Rača, this may be attributed to the presence of local employment opportunities, educational institutions, and access to urban services. Záhorská Bystrica, while more suburban in character, also shows indications of a stabilized daily regime. One potential contributing factor is the proximity of the Volkswagen automotive plant, which, although located just outside its cadastral boundaries, likely affects local mobile network fluctuations due to the high concentration of workers commuting to the facility. Collectively, these districts reflect a hybrid urban-suburban character, wherein the co-existence of residential, institutional, and service-oriented functions contributes to a more stable daytime population presence than would be expected in purely residential peripheries.

*Chronopolis C: Regime of bedroom suburbia.* One of the identified clusters of municipalities with a common weekly regime of population presence represents a key *chronopolis* in the context of this study. Its significance lies not only in the fact that it includes the second largest number of municipalities, but also in undergoing the most dynamic spatial and functional transformations. This is evidenced by the highest number of completed housing units among all identified chronopolises, indicating an intensive suburbanization process. Formerly agriculturally-oriented villages are being transformed into modern suburbs, often marked by monotonous layouts of detached single-family homes (Šveda, Boris, 2020).

This cluster is also unique in that fluctuations in mobile network user activity consistently peak only during nighttime hours throughout the entire week. A defining

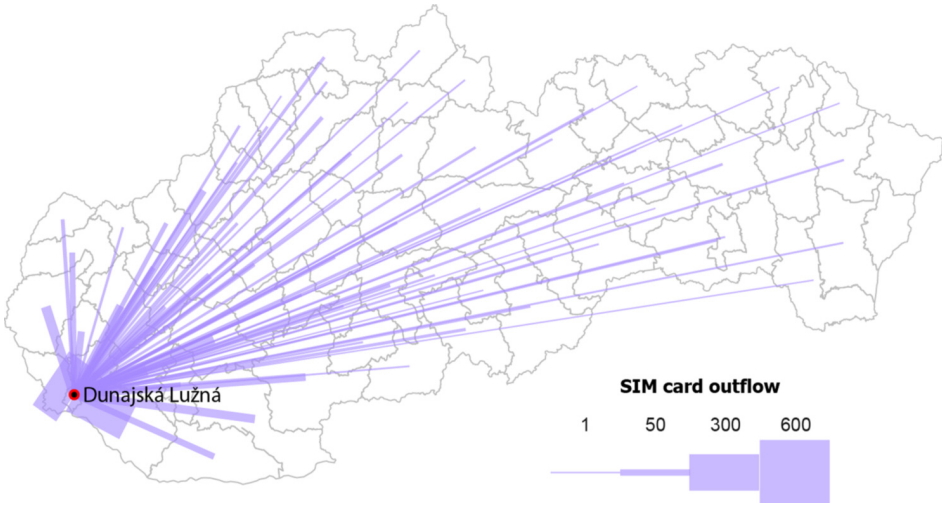


*Fig. 4: Saturday outflows of mobile phone users in the municipality of Dunajská Lužná (Chronopolis C). Data source: Slovak Telekom, 2023.*

feature is the substantial daytime decline in SIM card counts – up to 30% compared to the reference nighttime level. This phenomenon is not entirely unexpected, as these areas primarily serve as monofunctional residential zones or "bedroom communities" with a strong dependency on commuting to core cities and employment centers. They lack sufficient infrastructure and amenities to support greater daytime population retention.

However, a key and rather unique observation is the additional decline in mobile network users during weekends. This reduction begins on Friday evening and reaches 10–15% below the weeknight baseline, marking the most significant weekend decrease observed across all identified chronopolises. While the exact reasons for this trend remain unclear, it can be hypothesised that these newly developed suburban areas around Bratislava (and to some extent Trnava) do not offer an environment attractive enough to retain or draw visitors during weekends. On the contrary, part of the resident population seems to leave these relatively unappealing suburban settings over the weekend.

Whether suburban residents spend their weekends in the urban core or seek leisure opportunities in other regions of Slovakia remains an open question. Preliminary insights from SIM card mobility flows over the weekend suggest movements not only toward the core city but also into various parts of the country (Fig. 4). Whether this represents leisure-driven mobility or weekend "returns home" for personal regeneration cannot be determined from the available data. Nonetheless, it presents an intriguing topic for further in-depth research.

*Chronopolis D: Weekend regeneration in natural settings.* Similar to the previous chronopolis, Chronopolis D is characterised by a marked decline in the number of

active SIM cards during weekdays, indicating limited daytime population presence likely due to outbound commuting or low local employment opportunities. However, it differs notably in its weekend regime, which is marked by a substantial increase in user presence – pointing to a distinct recreational function.

This chronopolis comprises two partially distinct subgroups of municipalities that share a common peripheral location – both in relation to the metropolitan region and the urban core – and an attractive natural environment, yet differ in the nature of their weekend use. The first group includes municipalities typically associated with second-home ownership, where a significant portion of the housing stock is used seasonally. These include villages located in scenic submontane or forested environments such as Sobotište, Buková, and Prašník, or within floodplain landscapes like Vojka nad Dunajom and Bodíky. In these cases, the weekend surge in SIM card activity is most likely driven by second-home users, who arrive on Friday evenings and remain through the weekend.

The second group consists of municipalities that serve primarily as day-trip destinations for visitors engaged in leisure activities such as cycling, hiking, or nature-based recreation. These include, for example, Hamuliakovo and Smolenice, and also some semi-rural districts of Bratislava, such as Devín, and Čunovo. In these locations, mobile network activity increases only during daytime hours on weekends, with no significant overnight presence, indicating short-term visitation rather than overnight stays.

This interpretation is supported by the comparison of SIM card dynamics between two illustrative examples: Sobotište and the suburban district of Čunovo (Fig. 3e, 3f). In the rural setting of Sobotište, the number of mobile users increases substantially on Friday evening and remains elevated throughout the weekend nights, consistent with second-home use. In contrast, Čunovo shows increased activity only during Saturday and Sunday daytime, with nighttime levels remaining at or below weekday averages – characteristic of one-day recreational visits.

*Chronopolis E: Commuting periphery.* This chronopolis consists of municipalities that serve primarily as a residential hinterland for the metropolitan labour market. The defining temporal pattern of this cluster is a pronounced "U-shaped" curve in weekday mobile presence profiles – indicating a sharp outflow of population during the day due to commuting, followed by a return in the evening and overnight stabilisation (Fig. 3g).

What sets this chronopolis apart from others is the character of its weekend regime. Unlike clusters that experience an influx of second-home users or day-trippers, municipalities in Chronopolis E do not exhibit any substantial increase in mobile network activity over the weekend. The number of active SIM cards during weekend nights remains comparable to, or only slightly above, the reference level recorded during weekday nights.

**Ambivalent regime.** A final group of municipalities displays an ambivalent temporal regime that did not fit into any of the previously defined chronopolises.

This heterogeneous group includes both data-limited cases and functionally atypical patterns, making them analytically distinct.

A smaller subset within this group comprises very small settlements such as Šterusy and Povoda, where the total number of detected SIM cards is extremely low. These municipalities exhibit unstable or erratic daily rhythms, likely due to statistical volatility and limited representativeness in mobile data coverage. In such cases, the observed presence patterns cannot be interpreted with confidence.

Several municipalities classified as ambivalent display both morning and/or afternoon peaks in the number of active SIM cards. This pattern likely reflects their proximity to major transport corridors in the region – serving as key entry or transit points into Bratislava and other urban centres. Such dynamics are evident in locations like Jarovce and Chorvátsky Grob (see Fig. 3i), Ivanka pri Dunaji, or along transregional motorways traversing municipalities such as Zeleneč, Madunice, and Moravský Svätý Ján (see Fig. 3h). These areas diverge from standard commuter rhythms, suggesting complex patterns of mobility shaped by infrastructure-driven flows.

## Discussion and conclusion

The typology of chronopolises presented in this study contributes to the growing body of literature exploring urban and suburban rhythms using mobile phone data (e.g. Ahas et al., 2010; Nemeškal et al., 2020; Marada, Zévl, Petříček, Blažek, 2023; Stražovec et al., 2025). While the overall patterns of daytime depopulation in commuter zones or balanced activity in multifunctional urban districts mirror those observed in cities like Prague and Tallinn, the present study offers several distinct analytical and methodological advances.

First, the study introduces a flexible, rhythm-based typology of metropolitan space, rooted in chronogeographic theory and operationalised through bottom-up fuzzy clustering of weekly time-series data. This approach reveals non-obvious temporal regimes that challenge simplified core–periphery models. Notably, the inclusion of differentiation within the suburban zone of Bratislava demonstrates the framework's capacity to detect subtle yet functionally significant temporal distinctions. From a methodological standpoint, the application of fuzzy time-series clustering represents a key contribution. This technique enables the identification of rhythmically coherent groups without forcing strict boundaries and only assigns high-confidence profiles to chronopolises with clearly interpretable regimes. Municipalities with unstable or structurally ambiguous rhythms are purposefully left unclassified, ensuring both robustness and interpretive clarity.

Second, this research elevates weekend dynamics as an essential component of suburban rhythms analysis. While prior studies (Nemeškal et al., 2020; Šveda et al., 2020a) have focused on weekday commuting flows, this study reveals a wider spectrum of weekend patterns – ranging from regeneration-oriented inflows in second-home

areas, to residual presence in day-trip leisure zones, and even negative weekend effects in some suburban communities (*Regime of bedroom suburbia*). The identification of a regime marked by a chronopolis with declining weekend presence reflects the monofunctional character of certain rapidly suburbanizing municipalities, which lack the amenity structure and place attachment needed to retain residents during weekends. Recent research by Stražovec et al. (2025), which examines daily rhythms across the entire week, including weekends, provides complementary evidence for the importance of capturing full-week temporal variation in population presence.

Third, the findings offer empirical insight into the temporal impacts of new work arrangements. Several municipalities, particularly in suburban areas around Bratislava, display a distinct "Friday effect" – a lower-than-expected daytime decline in SIM card presence compared to other weekdays. This pattern may signal the increasing uptake of remote work, flexible hours, or compressed workweeks, which allow residents to remain locally anchored at the end of the workweek. Similar shifts in daily rhythms have been documented in other urban contexts, where the expansion of teleworking and "smart working" practices led to measurable changes in presence and mobility patterns (Woźniak-Jęchorek, Kuźmar, Bole, 2024; Nelson, Frost, 2023). While these signals are currently moderate and unevenly distributed, they suggest a gradual decoupling of residential rhythms from strict dependency on the urban core, potentially marking the early emergence of more autonomous or hybrid suburban chronotopes.

Overall, the proposed framework illustrates that suburban and rural hinterlands are not temporally homogeneous, but rather form a differentiated mosaic of rhythmic regimes – some shaped by workday influxes, others by leisure-driven weekend surges, and still others by infrastructural positioning. The Bratislava case thus serves as both a mirror and extension of similar metropolitan studies, and offers a transferable model for chronotopic classification.

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