Anatolii KORNUS



Scientific monograph

Cartographic Modelling of Settlement Transport Accessibility

Graph-Based Centrality Analysis and Time-Based Isochrone Mapping of Territorial Communities in Sumy Oblast, Ukraine

Recommended for printing by the Academic Council
of Sumy State Pedagogical University
named after A.S. Makarenko

Anatolii Kornus

CARTOGRAPHIC MODELLING OF SETTLEMENT TRANSPORT ACCESSIBILITY

Graph-Based Centrality Analysis and Time-Based Isochrone Mapping of Territorial Communities in Sumy Oblast, Ukraine

Scientific monograph

FOR AUTHOR USE ONLY

Recommended for printing
by the Academic Council of Sumy State Pedagogical University
named after A.S. Makarenko

REVIEWERS:
Yevhen Ivanov – Doctor of Geographical Sciences, Professor, Head of the Department of Constructive Geography and Cartography of Ivan Franko National University of Lviv;
Yurii Kyseliov – Doctor of Geographical Sciences, Professor, Head of the Department of Geodesy, Cartography and Cadastre of Uman National University;
Viktoriia Yavorska – Doctor of Geographical Sciences, Professor at the Department of Economic and Social Geography and Tourism, Dean of the Faculty of Geology and Geography of Odesa I.I. Mechnikov National University.

Imprint
Any brand names and product names mentioned in this book are subject to trademark, brand or patent protection and are trademarks or registered trademarks of their respective holders. The use of brand names, product names, common names, trade names, product descriptions etc. even without a particular marking in this work is in no way to be construed to mean that such names may be regarded as unrestricted in respect of trademark and brand protection legislation and could thus be used by anyone.

FOR AUTHOR USE ONLY

Cover image: www.ingimage.com

Publisher:
Dodo Books Indian Ocean Ltd. and OmniScriptum S.R.L publishing group
120 High Road, East Finchley, London, N2 9ED, United Kingdom
Str. Armeneasca 28/1, office 1, Chisinau MD-2012, Republic of Moldova, Europe

Managing Directors: leva Konstantinova, Victoria Ursu
info@omniscriptum.com

Printed at: see last page
ISBN: 978-620-9-47969-4

Copyright © Anatolii Kornus
Copyright © 2026 Dodo Books Indian Ocean Ltd.
and OmniScriptum S.R.L publishing group

CONTENT

PREFACE 7
Introduction 9
CHAPTER 1. TRANSPORT ACCESSIBILITY IN HUMAN GEOGRAPHY: THEORETICAL AND EMPIRICAL FOUNDATIONS 13
1.1. Transport accessibility and centrality in international human geography and transport studies 13
1.2. Conceptualisations and empirical studies of transport accessibility in Ukrainian geographical research 17
CHAPTER 2. METHODOLOGY 25
2.1. Study Area 26
2.2. Data Sources 27
2.3. Graph Construction and Network Modelling 28
2.4. Graph Connectivity Characteristics 30
2.5. Centrality Measures 33
2.6. Isochrone Modelling 36
2.7. Rationale & Methodological Limitations 37
CHAPTER 3. GRAPH-TOPOLOGICAL AND CONNECTIVITY-BASED ANALYSIS OF THE TRANSPORT NETWORK 41
3.1. Assessment of Transport Accessibility Based on Graph Topological Distance Analysis 42
3.2. Assessment of Transport Accessibility Based on Graph Connectivity Measures 47
CHAPTER 4. TRANSPORT ACCESSIBILITY ANALYSIS BASED ON GRAPH CENTRALITY MEASURES 53
4.1. Centrality and Transport Accessibility of District Centres 53
4.2. Analysis of Transport Accessibility Based on Graph Centrality Measures 57
4.2.1. Degree centrality 58
4.2.2. Closeness Centrality 62
4.2.3. Betweenness centrality 67
4.2.4. Eigenvector centrality 72
4.3. Comparative Synthesis of Centrality Metrics: A Two-Layer Structure of Transport Centrality 77
4.4. Integrated Interpretation of Transport Accessibility Patterns: Core–Transit–Periphery Model 86

FOR AUTHOR USE ONLY

4.4.1. Structural hierarchy of the transport network 86
4.4.2. Transit belt and secondary integrative centres 87
4.4.3. Peripheral zone and structurally weak nodes 87
4.4.4. Human geography implications 88
4.4.5. Synthesis and planning relevance 88
4.5. Typology of Community Centres Based on *Dc–Cc–Bc–Ec* Metrics 89
CHAPTER 5. LINKING CENTRALITY MEASURES WITH ISOCHRONE-BASED ACCESSIBILITY 95
5.1. Isochrone-based modelling of automobile transport accessibility 96
5.2. Interpretation of the Consistency between Network Centrality and Isochrone-Based Accessibility 102
5.3. Policy and Planning Implications 106
5.3.1. Differentiated Planning Strategies Based on Centrality Classes 106
5.3.2. Managing Transit Nodes and Preventing Network Bottlenecks 107
5.3.3. Addressing Peripheralization and Accessibility Inequalities 107
5.3.4. Reconsidering the Role of District Centres in Spatial Planning 108
5.3.5. Infrastructure Resilience and Strategic Redundancy 108
5.3.6. Methodological Implications for Transport Planning Practice 109
Conclusions 111
REFERENCES 115

FOR AUTHOR USE ONLY

PREFACE

This monograph is the result of long-term reflection on the role of transport accessibility in shaping regional space and everyday mobility. While transport networks are often analysed through technical or economic lenses, this study approaches accessibility primarily as a geographical phenomenon – one that structures territorial relations, influences patterns of interaction between settlements, and conditions the opportunities available to local communities.

The research presented in this book emerged from empirical work on the transport system of Sumy Oblast in north-eastern Ukraine. This region combines a distinct regional centre with a dispersed network of territorial community centres, many of which are characterised by limited connectivity and uneven access to key services. These spatial characteristics, intensified by administrative reforms and broader socio-economic transformations, raise fundamental questions about centrality, peripherality, and spatial integration at the regional level.

FOR AUTHOR USE ONLY

The motivation for this monograph lies in the need to move beyond simplified notions of distance and proximity. Real transport accessibility – understood through actual travel times and network structures – provides a more accurate representation of how space is experienced and utilised. By applying graph-based methods and isochrone analysis, the study seeks to reveal the hidden structure of the regional transport network and to identify those nodes and corridors that play a disproportionate role in maintaining spatial cohesion.

Although the empirical focus is on Sumy Oblast, the conceptual framework and methodological approach developed in this book are not region-specific. The issues discussed here – uneven accessibility, functional centrality, and the vulnerability of peripheral areas – are relevant to many regions characterised by low population density, inherited infrastructure, and ongoing territorial restructuring. In this sense, the monograph aims to contribute to broader debates in human geography and transport geography concerning spatial justice, regional development, and the role of infrastructure in shaping territorial futures.

This book is addressed to geographers, spatial planners, and researchers interested in transport systems and regional development, as well as to practitioners involved in territorial governance and infrastructure planning. It is hoped that the results presented here will not only enrich academic discussion, but also support more informed decision-making in the context of regional development and post-war recovery.

FOR AUTHOR USE ONLY

Introduction

Transport accessibility should be understood not merely as a technical characteristic of transport infrastructure, but as a socially significant territorial resource and a key condition for regional development [1, p. 91]. From the perspective of human geography, accessibility reflects the capacity of populations to participate in economic, social, and institutional life, shaping everyday mobility, opportunities for employment and education, and access to essential public services. Consequently, transport accessibility plays a critical role in structuring spatial inequalities and influencing patterns of territorial cohesion.

In regions characterised by low population density and an uneven spatial distribution of infrastructure, deficiencies in transport accessibility tend to reinforce peripheralisation processes. Limited connectivity between settlements constrains functional linkages, increases travel time to administrative, educational, medical, and economic centres, and reduces the overall efficiency of regional transport systems. Such conditions may lead to the marginalisation of smaller settlements and deepen socio-spatial disparities within regions.

FOR AUTHOR USE ONLY

Sumy Oblast, located in north-eastern Ukraine, represents a territorially complex case shaped by both natural conditions – such as the river network and forest-steppe landscape – and the historically inherited settlement pattern. The region's transport network has evolved unevenly, reflecting long-term differences in economic development, administrative status, and infrastructural investment. In the context of Ukraine's administrative-territorial reform, which involves the consolidation of territorial communities and a reconfiguration of governance at the local level, transport accessibility has become a crucial factor in redefining core – periphery relations and ensuring the functional viability of newly established communities.

From a human-geographical perspective, the relevance of analysing transport accessibility in the Sumy Oblast is closely linked to issues of spatial justice and equitable access to services. Uneven accessibility may result in reduced population mobility, limited access to labour markets and social infrastructure, and the social

isolation of peripheral and rural settlements. These processes are particularly significant in border and post-conflict regions, where transport networks play an important role in socio-economic resilience and regional recovery.

The application of graph-theoretical approaches and isochrone modelling provides an analytical framework for capturing the structural properties of transport networks and their implications for human mobility. By examining network connectivity, centrality, and travel-time accessibility, it becomes possible to identify structurally advantaged and disadvantaged areas, reveal infrastructural bottlenecks, and assess the degree of territorial integration at the regional scale.

Thus, the study of transport accessibility of district centres and centres of territorial communities in the Sumy Oblast extends beyond technical transport analysis. It contributes to a broader human-geographical understanding of spatial organisation, core – periphery dynamics, and territorial cohesion, offering an empirical basis for transport planning, regional policy-making, and strategies aimed at enhancing spatial integration and social equity.

FOR AUTHOR USE ONLY

Within human geography, transport accessibility is increasingly interpreted as a relational concept rather than a purely physical one. It reflects not only the presence of transport links, but also the spatial organisation of settlements, the hierarchy of centres, and the intensity of interactions between them. Accessibility therefore mediates everyday spatial practices, shaping how individuals and communities engage with space, time, and institutional structures. From this perspective, transport networks act as frameworks within which social and economic relations are reproduced and transformed.

The spatial configuration of transport networks plays a particularly important role in regions where historical development has produced asymmetric settlement systems. In such contexts, accessibility is unevenly distributed, reinforcing long-established core – periphery patterns. Larger urban centres tend to accumulate infrastructural advantages, while smaller and more remote settlements remain structurally dependent on a limited number of connections. This dependency increases

their vulnerability to disruptions and constrains their capacity for autonomous development, a pattern frequently observed in peripheral and border regions.

Assessing transport accessibility at the regional scale also allows for a more nuanced understanding of territorial cohesion. While formal administrative integration may suggest spatial unity, functional integration depends on the actual ability of populations to move, interact, and access services within reasonable time thresholds. Transport accessibility thus becomes a key indicator of how effectively territorial communities are embedded within regional systems, revealing discrepancies between administrative boundaries and functional spatial relationships.

In the Ukrainian context, these issues acquire additional significance due to ongoing processes of territorial restructuring and socio-economic transformation. The consolidation of territorial communities has altered patterns of service provision and governance, increasing the importance of reliable transport connections between local centres and regional hubs. In this setting, insufficient accessibility may limit the intended benefits of decentralisation, particularly for rural and semi-peripheral communities, by restricting access to administrative functions and essential services.

FOR AUTHOR USE ONLY

Finally, the relevance of transport accessibility analysis extends beyond routine spatial planning. In regions affected by military conflict and infrastructural stress, transport networks influence resilience, recovery potential, and long-term regional stability. Understanding the structural properties of regional transport systems, including their central and peripheral components, provides valuable insights for post-crisis reconstruction strategies and for reducing spatial inequalities that may otherwise intensify under conditions of external pressure.

This study focuses on the real transport accessibility of territorial community centres within Sumy Oblast, located in north-eastern Ukraine. The analysis is based on actual road connections and travel-time relations between settlements, rather than on abstract Euclidean distances or purely administrative proximity. Such an approach allows accessibility to be interpreted as a functional characteristic of the regional space, reflecting everyday mobility conditions and the practical ability of residents to reach key administrative and service centres.

Sumy Oblast represents a particularly informative case for analysing transport accessibility at the regional level. Its settlement system combines a clearly pronounced regional centre with a dispersed network of small and medium-sized towns and rural communities. The region's border location, relatively low population density, and inherited transport infrastructure create conditions in which differences in accessibility are especially visible. By examining the accessibility of community centres within this real transport network, the study captures how centrality and peripherality are produced through network structure and travel-time constraints, rather than through formal territorial status alone.

* * *

FOR AUTHOR USE ONLY

CHAPTER 1. TRANSPORT ACCESSIBILITY IN HUMAN GEOGRAPHY: THEORETICAL AND EMPIRICAL FOUNDATIONS

Transport accessibility has long been recognised as a fundamental spatial attribute within human geography, shaping the organisation of settlements, the distribution of economic activities, and patterns of social interaction. Beyond its technical dimension, accessibility serves as a relational concept that links transport networks with human behaviour, socio-economic opportunities, and regional development processes. Classic and contemporary scholarship emphasises that transport accessibility is inherently multidimensional, encompassing infrastructural, spatial, temporal, and social components. From Hansen's seminal conceptualisation of accessibility as "potential opportunities for interaction" (Hansen, 1959) [] to recent network-theoretical and GIS-based approaches, research has highlighted the interplay between network configuration, settlement structure, and population mobility. Particularly in peripheral and sparsely populated regions, variations in accessibility can produce pronounced inequalities, influencing local development trajectories, service provision, and territorial cohesion. This chapter provides a comprehensive synthesis of theoretical and empirical contributions, situating the analysis of Sumy Oblast within broader debates on accessibility, spatial justice, and human-geographical reasoning.

FOR AUTHOR USE ONLY

1.1. Transport accessibility and centrality in international human geography and transport studies

Within human geography, transport accessibility has long been conceptualised as a key spatial attribute shaping socio-economic processes, settlement systems, and regional development. One of the foundational contributions is Hansen's seminal work, which defined accessibility as the "potential of opportunities for interaction" and demonstrated its influence on land-use patterns and spatial organisation [2]. This conceptualisation established accessibility not merely as a technical transport indicator,

but as a relational geographic concept linking transport systems with social and economic structures.

Subsequent research expanded this approach by integrating accessibility into regional and urban geography, emphasising its role in shaping spatial inequalities. Geurs and van Wee (2004) proposed a comprehensive conceptual framework distinguishing between infrastructure-based, location-based, person-based, and utility-based accessibility measures, thereby highlighting the multidimensional nature of accessibility in spatial analysis [3]. Their work underlined that accessibility outcomes depend not only on network configuration but also on socio-demographic characteristics and spatial distribution of activities – an aspect highly relevant for peripheral and sparsely populated regions such as Sumy Oblast.

A significant body of research has also addressed the relationship between transport accessibility and social equity, a central concern in contemporary human geography. Preston and Rajé (2007) examined transport accessibility through the lens of social exclusion, demonstrating how limited connectivity can exacerbate marginalisation of rural and peripheral communities [4]. Their findings resonate strongly with Ukrainian regional contexts, where declining transport services and uneven infrastructure provision contribute to spatially differentiated life chances.

FOR AUTHOR USE ONLY

Isochrone-based approaches, increasingly applied in accessibility studies, have been widely used to visualise spatial disparities in travel time and service provision. Apparicio et al. (2008) demonstrated the effectiveness of isochrone mapping for identifying inequalities in access to urban services, particularly healthcare, highlighting its relevance for policy-oriented spatial planning [5]. Another article by Apparicio et al. (2017) is an updated review of spatial access assessment methods, which examines different types of distances and their impact on accessibility assessment [6]. Such approaches align methodologically with the present study, where travel-time thresholds are used to assess real transport accessibility of community centres.

From a network-analytical perspective, the integration of graph theory into transport geography has enabled more nuanced interpretations of spatial structure and functional centrality. Transport networks are increasingly analysed as complex systems

in which centrality measures capture different dimensions of spatial importance and vulnerability. Scholars emphasise that centrality metrics – such as degree, betweenness, closeness, and eigenvector centrality – provide insights into both structural cohesion and functional dominance within transport systems, particularly in regional-scale analyses (e.g. Porta et al., 2006; [7]). These approaches allow identification of critical nodes whose disruption could significantly affect overall network performance, an issue of heightened relevance in conflict-affected regions.

Recent literature also highlights the growing importance of transport accessibility analysis in post-socialist and transition economies, where inherited spatial structures and underinvestment in infrastructure have produced pronounced regional disparities. Studies conducted in Central and Eastern Europe emphasise that accessibility patterns often reinforce historical core – periphery structures and pose challenges for territorial cohesion and balanced regional development. In this context, transport accessibility research serves not only analytical but also normative functions, informing spatial justice, regional policy, and infrastructure prioritisation.

FOR AUTHOR USE ONLY

In regional transport planning and modelling, accessibility indicators have traditionally played a central role. However, contemporary challenges require the development of new methodological approaches that ensure high computational efficiency, multi-scalarity, transparency, and adaptability, while relying on open and heterogeneous data sources describing transport networks with high spatial resolution across extensive geographical areas. The study by [8] introduces *UrbanAccess*, an open-source tool based on a generalised and scalable methodology for assessing transport accessibility. *UrbanAccess* enables the analysis of multimodal networks by integrating pedestrian infrastructure and schedule-based public transport services at a high spatial resolution within metropolitan areas. The practical application of the tool is demonstrated through a case study assessing regional public transport accessibility in the San Francisco Bay Area (California).

The study by [9] emphasises the importance of spatial accessibility for shaping local transport policy, as it allows territorial disparities to be identified and supports more effective infrastructure allocation. The authors analyse methodological

improvements in accessibility measurement and identify two major research trends: multimodal accessibility and temporal variations in spatial accessibility. The study highlights the need for deeper involvement of geographers in integrating dynamic data and strengthening the influence of accessibility analysis on decision-making processes.

An original example of geoinformation-based cartographic representation of transport accessibility is the *TUM Accessibility Atlas* for the Munich metropolitan region [10], which focuses on addressing transport and land-use accessibility challenges under conditions of rapid population growth. The atlas integrates diverse scientific approaches to accessibility measurement, including multimodal transport networks and structural land-use data. Its primary objective is to visualise spatial and socio-economic disparities, support improved regional planning and development, and establish a shared analytical framework among stakeholders addressing sustainable development challenges.

FOR AUTHOR USE ONLY

The study by [11] develops a novel method for measuring accessibility circuity in urban environments, accounting for street network efficiency between different types of urban destinations. Unlike traditional approaches that assess accessibility solely through proximity or transport density, the proposed *pairwise circuity* (PC) metric measures excess travel costs arising from street network structure. This approach captures both spatial and topological correlations between locations, making it flexible for comparative analyses. The results reveal statistically significant relationships between PC and indicators of urban prosperity and accessibility, enabling clear differentiation of cities by development level and geographical context.

The study by [12] addresses spatial accessibility to healthcare services by developing a geoprocessing toolbox for ArcGIS Pro implementing both classical and enhanced versions of the two-step floating catchment area (2SFCA) method. The methodology integrates distance buffers and travel-time catchments, allowing flexible assessments based on user-defined preferences. A case study on haemodialysis services in Tennessee revealed substantial accessibility disparities, with urban areas exhibiting higher accessibility than rural and suburban zones. Importantly, the analysis incorporated age-weighted population estimates to account for non-spatial factors

influencing service accessibility. The freely available tools provide a valuable resource for researchers and policymakers seeking to improve equity in healthcare access.

The article by [13] discusses the use of emerging data sources – such as GPS traces, smartphones, and smart cards – to enhance accessibility analysis. The authors stress that high spatial and temporal resolution data enable more accurate assessments of population mobility, travel speeds, and travel times. The study also examines the use of digital platforms such as Google Maps and OpenStreetMap to improve measurement accuracy. The article reviews eight empirical studies demonstrating innovative approaches to accessibility analysis, particularly through the application of big data and novel methodologies.

The study by [14] examines the relationship between individual health-related behaviours and spatial accessibility to relevant facilities, proposing a regional-scale measurement approach based on aggregated data. The authors highlight the critical role of distance to urban centres and argue for multidimensional accessibility assessments that integrate travel behaviour. These findings have important implications for public health policy, underscoring the need to consider both residential and non-residential factors when evaluating healthcare accessibility.

FOR AUTHOR USE ONLY

1.2. Conceptualisations and empirical studies of transport accessibility in Ukrainian geographical research

Within Ukrainian geographical research, the concept of *transport accessibility* has been interpreted in several ways. For instance, the study by Puhach and Novosad argues that, from the perspective of human geography, transport accessibility as an indicator of societal spatial opportunities is more accurately described using the concept of *transport discrimination* [15]. According to the authors, this term has a broader conceptual scope and better captures territorial inequalities in access to transport services. Mazurova and Virchenko define transport discrimination as the spatial limitation of transport services within a given territorial unit – whether a country, region, district, city, or village – resulting from insufficient transport network

development [16]. Such discrimination restricts equality in access to quality transport services, reduces population mobility, diminishes competitiveness, and increases time and financial costs associated with travel.

In the present study, however, the term *transport accessibility* is retained, as the primary focus lies on the quantitative assessment of transport network structure and the spatial organisation of inter-settlement connections. Since the research emphasises, structural characteristics derived from graph modelling, node centrality analysis, and isochrone-based accessibility assessment – rather than socio-economic inequalities – the term *transport accessibility* is considered more appropriate and analytically neutral. While *transport discrimination* implies a normative socio-economic evaluation, the chosen terminology allows for an objective description of mobility opportunities within the territory.

A substantial body of Ukrainian scholarship has addressed transport accessibility at national, regional, and local scales. Anisimova et al. [17] propose a methodological approach to assessing suburban recreational areas along the Siverskyi Donets River based on transport accessibility. The authors emphasise that accessibility is a key determinant of recreational value at the local level, incorporating distance, road quality, and travel time into their evaluation framework.

FOR AUTHOR USE ONLY

A thematically related study by Anisimov [18] develops classification and scoring schemes to assess the location of recreational areas relative to settlements and alternative road access options. The research covers six potential recreational sites along the Siverskyi Donets River within Kharkiv Region.

The study by Baiteryakov and Voronova [19] focuses on the identification of spatial patterns and disparities in automobile transport accessibility within Zaporizhzhia Oblast. The authors constructed and analysed graphs representing the region's road networks and its administrative districts. For each graph, corresponding matrices were created specifying shortest distances. Based on these calculations, the level of automobile transport accessibility of administrative units was evaluated and compared.

Barskyi et al. [20] investigated transport accessibility in the city of Lutsk using isochrone analysis, which enables the assessment of access to key transport infrastructure objects. The authors highlighted uneven accessibility between different districts, caused both by the density of the road network and the organisation of traffic flows. This analysis allows identification of zones with limited accessibility and provides recommendations for improving transport planning, which is particularly relevant in the context of enhancing population mobility and public transport efficiency.

O. Dzubinska et al. [21] examined the impact of transport infrastructure on the development of the regional tourism and recreation sector. They emphasised that the quality of transport connectivity is a key factor determining the accessibility of recreational facilities. Main indicators for assessing the transport network included road type, density, travel speed, network length, road category, capacity, and average daily traffic intensity. The study provided a comparative analysis of road density and categories between Volyn Oblast and Ukraine as a whole. A methodology was proposed for assessing transport provision for recreational zones, considering operational network length and regional population, which allows evaluation of transport provision dynamics during peak holiday periods.

FOR AUTHOR USE ONLY

O. Zahurskyi [22] analysed various approaches to assessing transport accessibility, considering it as an institutional category reflecting the interrelation of factors meeting the movement needs of people and goods. The author emphasised the need to develop a new methodological framework to adequately assess territorial differentiation in population quality of life, taking into account institutional changes. Special attention was given to transport provision in rural areas, where unstable road connections, irregular bus services, and poor road conditions lead to transport discrimination, limiting access to essential social services such as healthcare, education, and daily services.

A. Zauralska [23] proposed a methodology for assessing transport accessibility between elements of football club training bases (NTB), taking into account actual distances and speed limits within and outside the city. This approach allows the

determination of optimal NTB locations with a focus on minimising travel costs and time. Overall, the study provides practical recommendations on the placement and organisation of NTB, highlighting the importance of a comprehensive approach integrating urban planning and transport aspects.

O. Leiberiuk [24] examined the application of geospatial analysis to assess accessibility to medical services in the context of healthcare reform in Ukraine. The author detailed the steps of such analysis, including defining transport accessibility zones to hospital district centres at 15, 30, 45, 60 minutes, and beyond one hour (these time thresholds are also applied in our study). Special attention was given to the population distribution within these zones and their age structure, enabling the identification of potential inequalities in access to medical services. Furthermore, accessibility to centres of neighbouring hospital districts was investigated, providing important insights for planning an effective medical infrastructure and ensuring equitable access to quality healthcare for all population groups.

FOR AUTHOR USE ONLY

O. Matiichyk [25] proposed a novel approach to evaluating transport network efficiency through the lens of transport accessibility. The author developed a methodology allowing quantitative assessment of the efficiency of the automobile transport network, particularly for the Capital Economic Region of Ukraine. The results indicate a high efficiency of the road transport network in the studied region and highlight peripheral satellite towns, which can inform decisions on regional transport development. In a separate study by the same author [26], the multidimensionality of transport accessibility and its importance for effective transport system functioning is discussed. The study emphasises that traditional understanding of transport accessibility as time or distance is limited. Instead, multiple dimensions are considered, including temporal, individual, social, territorial, and economic aspects. Overall, this work underscores the importance of a comprehensive understanding and assessment of transport accessibility to ensure equitable mobility opportunities and promote socio-economic development of regions.

A. Mykhailov [27] analysed the influence of urban planning structure on transport accessibility in Donetsk, considering factors such as compactness of

settlement, spatial configuration, and layout of urban roads. The study determined compactness coefficients and the hierarchy of attraction centres within city districts. Results indicate that transport accessibility can be enhanced by redistributing population, optimally locating residential areas, increasing density near the city centre, and modifying road layouts to reduce network indirectness.

Silchenko et al. [28] explored how transport infrastructure affects socio-economic development in Kirovohrad Region. They highlighted that many settlements suffer from poor connectivity to administrative centres due to elongated territorial configuration, poor road quality, and irregular public transport. Such conditions result in transport-related discrimination, adversely impacting population mobility and access to social services.

M. Tomaschuk M. [29] examined the application of GIS to assess transport accessibility in the context of forming united territorial communities in Ukraine. A methodology for determining accessibility zones of potential administrative centres using buffer zones corresponding to normative requirements was proposed. The practical application was demonstrated for Kyiv Region, identifying 29 potential administrative centres. Results indicated that GIS-based analysis facilitates an objective and scientifically grounded approach to forming capable communities, ensuring optimal distribution of resources and services for the population.

FOR AUTHOR USE ONLY

Tretiak and Lepetiuk [30] investigated an algorithm for determining transport accessibility for designing tourist routes using GIS. OpenStreetMap data on tourist facilities and road networks were processed with PostgreSQL, QGIS, and GRASS GIS. The resulting isochrone maps visualise travel time distances from points of interest along the road network, supporting the optimisation of tourist routes and enhancing their attractiveness.

Ul et al. [31] proposed a methodology for modelling territorial transport accessibility using isochrones based on OpenStreetMap data, GRASS GIS, and PostgreSQL. The authors emphasised that developed transport infrastructure increases territorial value, influencing land, real estate, and social services. An isochrone map for Volyn Region showed that approximately 67% of the region could be reached from

key settlements within one hour. While the methodology can be applied to other regions, its effectiveness is limited without considering traffic intensity, road quality, and speed restrictions.

Yanovskyi and Matiichyk [32] studied different approaches for assessing passenger transport accessibility and proposed a systematisation of components and indicators for such assessment. They formalised the concept of integrated transport accessibility, enabling evaluation of the level of regional transport infrastructure development. The systematisation provides a framework for comprehensive assessment of regional transport systems and can inform planning and improvement strategies.

Within this research landscape, a series of studies by A. Kornus and co-authors further develop graph-theoretical and GIS-based approaches to transport accessibility, integrating quantitative network metrics with human-geographical interpretation. In one of these studies [33], transport accessibility is examined as a relational spatial property emerging from the configuration of regional transport networks. By applying graph representations and centrality measures, the authors demonstrate how network topology shapes functional linkages between settlements and influences patterns of regional connectivity.

FOR AUTHOR USE ONLY

Subsequent research extends this approach to the context of administrative-territorial reform in Ukraine [34]. Using centrality analysis and isochrone modelling, the authors assess accessibility to local administrative centres and reveal spatial inequalities associated with infrastructural constraints and institutional change. The study highlights the human-geographical consequences of uneven accessibility, including reduced mobility, limited access to public services, and the risk of socio-spatial marginalisation of peripheral communities.

A further contribution [35] focuses on the empirical assessment of real transport accessibility using time-based metrics derived from actual road networks. The application of degree, closeness, betweenness, and eigenvector centrality measures reveals hidden hierarchies within regional transport systems, demonstrating that administrative status does not necessarily correspond to structural importance within

the network. These findings underscore the value of combining formal network analysis with territorial interpretation.

Taken together, the reviewed international and Ukrainian literature demonstrates that transport accessibility has evolved into a mature and conceptually rich research field within human geography, combining theoretical reflection with diverse methodological approaches. International scholarship has established accessibility as a relational and multidimensional spatial concept, closely linked to network structure, centrality, and socio-spatial differentiation, and has developed a wide range of analytical tools – from graph-theoretical metrics to isochrone-based and multimodal accessibility models. Ukrainian geographical research, in turn, provides extensive empirical insights into accessibility patterns at national, regional, and local scales, particularly in relation to administrative-territorial organisation, public service provision, and sectoral development. However, these studies often remain fragmented territorially and methodologically, and comprehensive region-wide analyses based on real travel-time accessibility and formal network properties are still relatively scarce.

FOR AUTHOR USE ONLY

In this context, Sumy Oblast represents a particularly relevant yet insufficiently explored case. As a predominantly peripheral region with a heterogeneous settlement system and unevenly developed transport infrastructure, it offers a suitable empirical setting for integrating human-geographical interpretation with formal network analysis. The present study addresses this research gap by combining graph-theoretical measures of centrality with isochrone-based modelling of real transport accessibility to community centres. Such an approach makes it possible to reveal hidden spatial hierarchies within the regional transport network, assess the degree of functional integration of settlements, and move beyond purely normative interpretations toward an analytically grounded understanding of territorial connectivity and accessibility.

* * *

The review of existing literature demonstrates that transport accessibility cannot be understood solely as a function of distance or travel time. Instead, it must be interpreted

as a relational and context-sensitive attribute, shaped by both the physical configuration of networks and the socio-economic characteristics of populations. Empirical studies across Ukraine and other post-socialist regions illustrate the critical role of accessibility in mediating regional disparities, social inclusion, and the efficiency of service provision. Methods ranging from isochrone mapping to graph-theoretical centrality metrics provide complementary perspectives, allowing researchers to capture structural patterns, functional hierarchies, and vulnerabilities within transport systems. However, despite substantial contributions, region-wide, node-specific analyses integrating real travel times, network topology, and community-level socio-spatial factors remain scarce, particularly for Sumy Oblast. This literature gap motivates the present study, which combines topological and travel-time analyses with centrality-based metrics to assess both potential and effective accessibility of community centres, thereby providing actionable insights for spatial planning and regional development policy.

FOR AUTHOR USE ONLY

CHAPTER 2. METHODOLOGY

The methodological framework of this study conceptualises transport accessibility as a multidimensional spatial property arising from the interaction between network structure, territorial organisation, and real-world mobility constraints. To capture this complexity, the research adopts a multi-stage approach that combines graph-theoretical analysis with travel-time-based modelling, allowing for the assessment of both structural (potential) and effective accessibility.

The methodology is grounded in human and transport geography, where accessibility is understood as a relational characteristic shaped by connectivity, hierarchy, and spatial embeddedness. Graph-based representations of the road network provide a formal framework for analysing these relationships, enabling the identification of central and peripheral positions, network cohesion, and structural vulnerabilities. The incorporation of weighted metrics and isochrone modelling further bridges the gap between abstract network structure and actual mobility conditions by accounting for distance, road hierarchy, and travel time.

FOR AUTHOR USE ONLY

The analysis relies on real-world transport data derived from official statistical sources and open geospatial datasets, ensuring empirical robustness and methodological transparency. All stages of graph construction, metric calculation, and spatial modelling are implemented using open-source tools, supporting reproducibility and comparability with similar regional studies.

The methodological design is explicitly informed by the territorial context of Sumy Oblast and the administrative-territorial reform implemented in Ukraine in 2020, which redefined the functional role of community and district centres. Accordingly, the analysis focuses on accessibility between these centres, reflecting the contemporary spatial logic of service provision and regional governance.

Overall, this chapter outlines a coherent methodological framework that integrates complementary analytical techniques to provide a robust basis for the subsequent assessment and interpretation of transport accessibility patterns in the region.

2.1. Study Area

The study focuses on Sumy Oblast, a predominantly rural and sparsely populated region located in north-eastern Ukraine, bordering Russia and the Chernihiv, Kharkiv, and Poltava regions. The oblast covers an area of approximately 23,800 km², accounting for about 4% of the national territory, and is characterised by relatively low population density and a dispersed settlement pattern. These spatial characteristics make transport accessibility a key factor shaping everyday mobility, access to services, and functional integration of settlements.

Administratively, Sumy Oblast underwent a profound transformation following the nationwide administrative-territorial reform implemented in 2020. As a result of this reform, the previous system of numerous districts (raions) and local councils was replaced by a more consolidated structure comprising five enlarged districts (raions) and a network of territorial communities (hromadas). This restructuring significantly altered the spatial hierarchy of administrative centres, redefining their functional roles and catchment areas. Many settlements lost their former district-centre status, while newly designated community centres became focal points for administrative, social, and economic services. These changes have had direct implications for transport demand patterns and the real accessibility of administrative and service centres, particularly in peripheral and rural areas.

FOR AUTHOR USE ONLY

The oblast comprises a network of district centres and territorial community centres, whose accessibility is critical for social and economic cohesion, especially under conditions of decentralisation and increased responsibility at the local level. Access to administrative services, healthcare, education, and markets is strongly dependent on the quality and configuration of inter-settlement transport links, making the spatial organisation of the transport network a central analytical concern.

The region's transport infrastructure has evolved under the combined influence of natural and historical factors. The territory is shaped by a dense river system, including the basins of the Psel, Vorskla, Sula, and Desna rivers, which historically influenced settlement location and road alignment. From a landscape perspective, Sumy Oblast spans two major natural zones: the mixed-forest zone in the northern part

and the forest-steppe zone, each presenting different constraints and opportunities for transport network development. Variations in relief, soil conditions, and land cover have contributed to uneven road density and quality across the region.

Historically, the settlement system of Sumy Oblast developed as a polycentric network of small and medium-sized towns, many of which originated as trade, administrative, or industrial nodes. However, post-Soviet economic restructuring, demographic decline, and chronic underinvestment in transport infrastructure have intensified spatial disparities in accessibility. These processes have reinforced core – periphery patterns, with stronger connectivity around regional and sub-regional centres and reduced accessibility in remote border and rural areas.

Understanding the spatial organisation of the transport network in Sumy Oblast is therefore particularly relevant in the context of administrative-territorial reform and decentralisation, which require reliable transport connections to ensure the effective functioning of enlarged communities. Against this background, the present study treats Sumy Oblast as a representative case for analysing real transport accessibility and centrality at the regional scale, where institutional change intersects with inherited spatial structures and infrastructural constraints.

FOR AUTHOR USE ONLY

2.2. Data Sources

The analysis employs real-world data on the inter-settlement road network within Sumy Oblast, with a specific focus on routes connecting district centres and territorial community centres. Road network data were sourced from official regional datasets, including materials provided by the State Statistics Service of Ukraine [38], and were complemented by OpenStreetMap and Google Maps extracts to ensure comprehensive coverage of minor roads and local connections that are often underrepresented in official statistics. To enhance data reliability, information from different sources was cross-checked and harmonised, particularly with regard to road classification, connectivity, and continuity of network segments. This integrative approach allowed the construction of a topologically consistent transport network, suitable for graph-theoretical analysis at the regional scale.

Each road segment was georeferenced and attributed with its length (in kilometres) and maximum allowed speed (km/h), enabling the calculation of travel time as the primary weight metric. Travel time was selected as the key indicator of accessibility, as it better reflects real mobility conditions than purely distance-based measures, especially in regions characterised by heterogeneous road quality and varying speed regulations. Where official speed limits were unavailable or ambiguous, values were assigned based on road category and functional importance, following standard transport geography practices.

The resulting dataset includes all district centres and territorial community centres, represented as 51 nodes connected by 74 primary road links, forming the backbone of the regional inter-settlement transport network. These nodes were selected due to their administrative and functional significance, as they serve as key points of access to public services, governance structures, and socio-economic activities under the post-2020 administrative-territorial framework.

FOR AUTHOR USE ONLY

Supplementary demographic and administrative data – including population size, settlement status, and administrative hierarchy – were incorporated to contextualise the spatial patterns observed in the network analysis. While these variables were not directly embedded in the graph weights, they provided an essential interpretative layer for understanding the human-geographical implications of transport accessibility and centrality patterns across the oblast.

Importantly, the dataset reflects pre-war transport conditions, allowing the analysis to capture the structural characteristics of the regional transport network as shaped by long-term spatial and institutional processes, rather than short-term disruptions. This ensures that the results remain relevant for strategic spatial planning and regional development discussions.

2.3. Graph Construction and Network Modelling

The transport network of Sumy Oblast was analysed using graph-theoretical methods, which provide a robust framework for examining topological and functional accessibility within spatial systems. In human geography, graph modelling allows

transport networks to be conceptualised not merely as physical infrastructures, but as relational spatial structures that shape inter-settlement interactions, service accessibility, and regional cohesion.

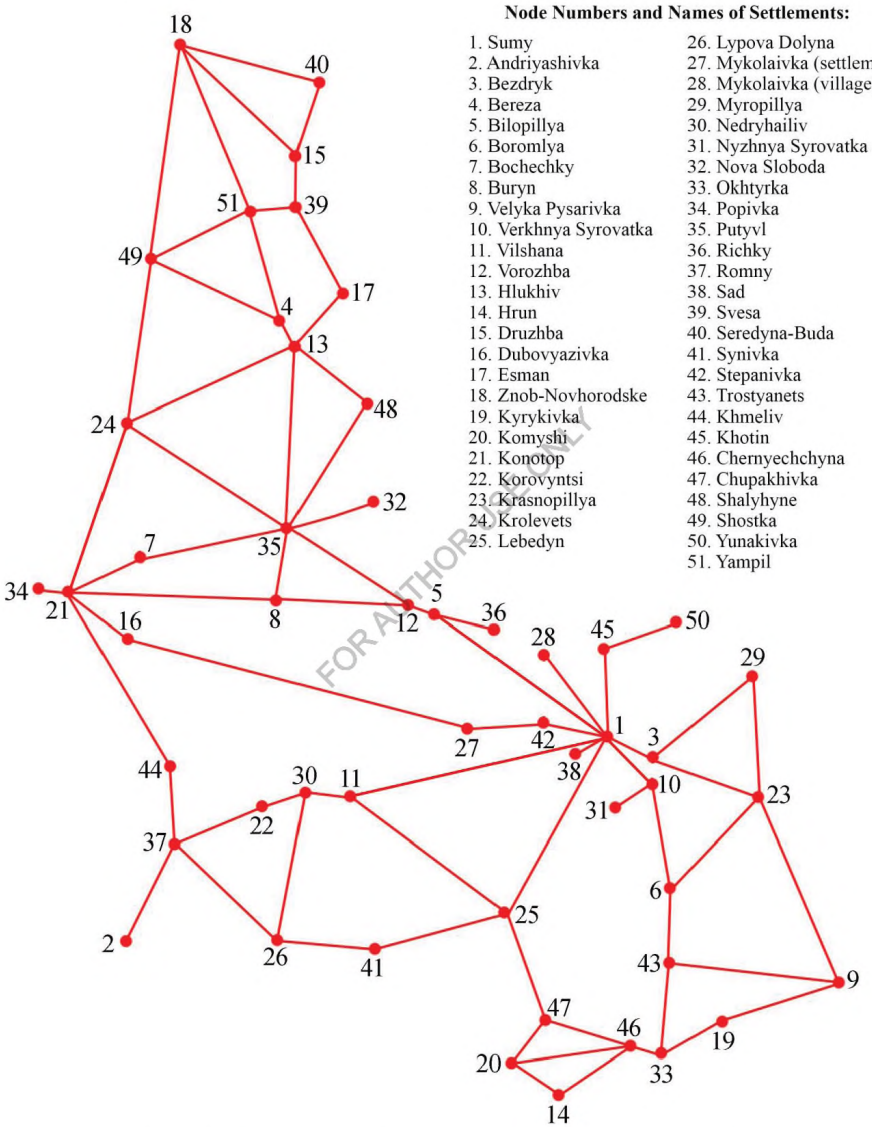


Fig. 1. Graph of the transportation network of the Sumy Oblast

Source: Own elaboration using Python-based graph analysis and geospatial data in Google Colab.

The regional transport network was modelled as a weighted, undirected graph $G = (V, E)$, where nodes correspond to district centres and territorial community centres (51), and edges represent direct road connections between them (74) (Fig. 1). An undirected structure was selected to reflect the bidirectional nature of road-based mobility under normal operating conditions, which is appropriate for regional-scale accessibility analysis.

Edge weights were assigned using two complementary approaches. First, a distance-based weighting scheme was applied to reflect differences in road quality and functional importance. Travel distances were expressed as "conditional kilometres", calculated by multiplying the physical length of each road segment by coefficients corresponding to road class (see 2.6). This approach allows the incorporation of qualitative differences in infrastructure into quantitative analysis and has been widely used in regional transport geography to approximate effective travel impedance.

Node coordinates were derived from geospatial datasets and verified against authoritative cartographic sources to ensure accurate spatial positioning. This allowed the transport network to be analysed both as a topological structure and as a spatially embedded system, facilitating the integration of graph metrics with cartographic representation.

FOR AUTHOR USE ONLY

All computations and visualisations were conducted in the Google Colab environment using the Python programming language. The NetworkX library was used for graph construction, while NumPy supported matrix operations and numerical processing. Visual outputs were generated using Matplotlib.

2.4. Graph Connectivity Characteristics

The assessment of transport accessibility based on graph connectivity characteristics represents an effective methodological approach for analysing the overall structure and integration of regional transport networks. Compared to distance- or time-weighted accessibility measures, this approach offers several important advantages that make it particularly suitable for generalised network analysis at the regional scale.

One of its key strengths lies in its conceptual simplicity and universality, as it enables the evaluation of topological properties of a transport system without the need to incorporate detailed weight parameters such as travel time, speed limits, or traffic intensity. By focusing on the structure of connections between nodes, graph connectivity indicators capture the intrinsic spatial organisation of the network and its potential to support inter-settlement interaction.

The use of indicators such as average shortest path length, clustering coefficient, graph density, network efficiency, and graph diameter makes it possible to obtain a synthetic overview of regional connectivity, assess the degree of network integration, and identify potential structural bottlenecks. These indicators are widely applied in transport geography, urban studies, and regional planning, as they are scalable and applicable to both local and large-scale transport systems.

Using the NetworkX library, a set of key topological characteristics describing graph connectivity was calculated. These include: a) Average shortest path length, representing the average number of steps required to travel between any pair of nodes in the network; b) Clustering coefficient, indicating the degree of local interconnectedness among neighbouring nodes; c) Graph density, expressing the ratio of existing connections to the maximum possible number of connections; d) Graph efficiency, interpreted as a measure of global accessibility; e) Graph diameter, defined as the longest shortest path within the network.

FOR AUTHOR USE ONLY

Graph density (D) was calculated using the following formula:

$$D = \frac{2E}{n(n-1)} \quad (1),$$

where E is the number of edges, and n is the number of nodes.

The average shortest path length (APL) was computed as the mean value of the shortest paths between all pairs of nodes in the graph:

$$APL = \frac{1}{n(n-1)} \sum_{i \neq j} d(i,j) \quad (2),$$

where n denotes the number of nodes in the graph and $d(i,j)$ represents the shortest path length between nodes i and j.

To assess the compactness and connectedness of the graph, the average distance (B) was calculated as the mean distance from a given node to all other nodes in the network. For node i, this measure is defined as:

$$B(v_i) = \frac{\sum_{j \neq 1}^{n} d(v_i, v_j)}{n-1} \quad (3),$$

where $d(vi, vj)$ is the shortest distance between nodes i and j, and n is the total number of nodes in the graph.

To verify whether the network contains isolated groups of nodes and to assess the level of local cohesion, the average clustering coefficient was calculated as the mean of all local clustering coefficients:

$$C = \frac{1}{n} \sum_{i=1}^{n} Ci \quad (4),$$

where C_i is the clustering coefficient of node i, defined as:

$$Ci = \frac{2E_i}{k_i(k_i-1)} \quad (5),$$

Here, E_i represents the number of connections between the neighbours of node i, and k_i denotes the degree of node i (i.e. the number of its neighbouring nodes).

FOR AUTHOR USE ONLY

The clustering coefficient provides insight into the local structure of the transport network, indicating whether settlements form tightly connected subgroups or remain weakly integrated within the broader regional system.

To evaluate how efficiently transport accessibility can be ensured between nodes, graph efficiency was calculated as a measure of global accessibility. This indicator is based on the principle that shorter distances between nodes contribute more strongly to overall network efficiency. The sum of these contributions is normalised by the total number of node pairs $n(n-1)$ to obtain an average value. Graph efficiency $E(G)$ is defined as:

$$E(G) = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{i,j}} \quad (6),$$

where n is the number of nodes in the graph, d_{ij} is the shortest path length between nodes i and j (measured in number of edges), and $\frac{1}{d_{i,j}}$ represents the efficiency of interaction between the nodes i and j.

2.5. Centrality Measures

To characterise the relative importance of nodes within the transport network, the study computes multiple graph centrality metrics such as Bavelas index (*Bi*); Beauchamp index (*Ri*); Degree centrality (*Dc*); Closeness centrality (*Cc*); Betweenness centrality (*Bc*); Eigenvector centrality (*Ec*). These metrics allow the identification of core, peripheral, and structurally critical nodes, providing insights into hierarchical organisation, potential bottlenecks, and redundancy within the network.

To assess the transport accessibility of district and community centres in Sumy Oblast, the Bavelas index was applied as a measure of nodal accessibility within the transport network. This index is calculated as the ratio between the sum of absolute accessibility indices of all nodes in the graph and the absolute accessibility index of a specific node. The approach allows individual settlements to be evaluated in relation to the overall network structure rather than in isolation.

FOR AUTHOR USE ONLY

To determine the shortest paths between all pairs of nodes, the Floyd-Warshall algorithm was implemented. Based on the resulting matrix of shortest path distances, absolute accessibility indices were calculated for each node, followed by the computation of the Bavelas and Beauchamp (Bosham) indices [36, 37]. In addition, mean values of each index were calculated to characterise the overall accessibility of the network.

According to [19], the Bavelas index (Bi) is calculated as:

$$Bi = \frac{\sum_{j=1}^{n} S_i}{S_i} \qquad (7),$$

where: Si denotes the absolute accessibility index of node i, n – is the total number of nodes in the graph.

This formulation is particularly suitable for the analysis of real transport networks, as it accounts for the overall configuration of the network and thus enables a more comprehensive interpretation of its topological structure. The index captures the relational nature of accessibility, emphasising how the accessibility of a given node compares to that of the network as a whole. Consequently, nodes with lower absolute

accessibility values (i.e. shorter cumulative distances to other nodes) obtain higher Bavelas index values, indicating a more advantageous position within the network.

While the Bavelas index evaluates a node in terms of its absolute accessibility relative to other nodes, the Beauchamp index (also referred to as the Bosham index) measures relative accessibility, reflecting how efficiently a node is connected to the rest of the network while explicitly accounting for the total number of nodes. This characteristic makes the index particularly useful for comparative analysis between different graphs or regions.

The Beauchamp index Ri is calculated as follows [19]:

$$Ri = \frac{n-1}{S_i} \quad (8),$$

where Ri is the Beauchamp index of node i, n is the number of nodes in the graph, and Si is the absolute accessibility index of node i, defined as the sum of the shortest path distances from node i to all other nodes in the network.

A node with a higher Beauchamp index is considered more central, as it exhibits greater efficiency with respect to the entire network. Such a node is characterised by a relatively smaller cumulative distance to other nodes and thus occupies a more favourable position within the network topology. Conversely, a lower Beauchamp index indicates a peripheral position or reduced transport accessibility, as the node is associated with a larger sum of distances to other nodes and therefore weaker integration into the network structure.

FOR AUTHOR USE ONLY

Degree centrality $C_D(v)$, is among the most intuitive connectivity metrics. It reflects the importance of a node based on the number of its immediate neighbours. For an undirected graph, degree centrality is defined as:

$$C_D(v) = \frac{\deg(v)}{n-1} \quad (9),$$

where $\deg(v)$ is the degree of node v (the number of its connections); n is the total number of nodes in the graph, and $n-1$ represents the maximum possible number of connections for a node.

Closeness centrality *Cc(v)* is a key connectivity metric quantifying how efficiently a given node interacts with the entire network. It reflects the average

proximity of a node to all other nodes, thereby indicating how quickly other locations in the network can be reached from that point. Mathematically, it is defined as:

$$C_C(v) = \frac{n-1}{\sum_{u \neq v} d(u,v)} \quad (10),$$

where n is the number of nodes in the graph, and $d(u,v)$ denotes the shortest path distance between nodes u and v.

Betweenness centrality $C_b(v)$ is one of transportation network analysis's most important connectivity metrics. It quantifies how frequently a given node lies on the shortest paths between other nodes in the network. For each node v, betweenness centrality is calculated as the sum of the proportions of all shortest paths between pairs of nodes s and t that pass through node v, and is given by the formula:

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\delta_{s,t}(v)}{\delta_{s,t}} \quad (11),$$

where s and t are all distinct pairs of nodes in the graph such that $s \neq v$ and $t \neq v$; σ_{st} denotes the total number of shortest paths between nodes s and t, and $\sigma_{st}(v)$ is the number of those paths that pass through node v.

FOR AUTHOR USE ONLY

Eigenvector Centrality (Ec) is a network connectivity metric that estimates the influence of a node not only by the number of its direct connections (degree), but also by the importance of its neighbouring nodes. In this sense, a node receives a higher *Ec* score if it is connected to other highly influential nodes. The Eigenvector Centrality of node x_i is defined by the following recursive formula:

$$x_i = \frac{1}{\lambda} \sum_{j \in n_i} A_{i,j} x_j \quad (12),$$

where x_i denotes the *Ec* score of node i; A_{ij} is an element of the adjacency matrix A, which equals 1 if there is a link between nodes i and j, and 0 otherwise; xj is the *Ec* score of the neighbouring node j; and λ is the largest eigenvalue of matrix A, used to normalise the centrality values.

Visualisation and interpretation of results were performed using Matplotlib and NetworkX libraries. All calculations and modelling were performed in Google Colab, which allowed interactive processing and visualisation of data.

2.6. Isochrone Modelling

To complement the analysis of network topology and graph-based centrality with a temporal perspective on accessibility, isochrone modelling was employed. Isochrone maps represent travel-time contours radiating from a selected source node – either a district centre or the regional hub of Sumy – and delineate areas that can be reached within predefined time intervals. This approach enables the assessment of real, time-based transport accessibility, bridging the gap between abstract network structure and everyday mobility conditions.

Initial estimates of travel time were based on the assumption of a constant average travel speed of 50 km/h, which provides a standardised baseline for regional-scale accessibility analysis. Shortest travel times from the central node to all other nodes in the network were calculated using Dijkstra's algorithm, which identifies optimal paths in a weighted graph through a greedy search procedure. At each iteration, the algorithm selects the node with the minimum current travel cost and updates distances to neighbouring nodes accordingly, ensuring the computation of shortest paths across the entire network.

FOR AUTHOR USE ONLY

Distances between settlements (graph nodes) were expressed in conditional kilometres, a metric designed to better reflect real travel conditions than purely geometric distances. This approach accounts for differences in road hierarchy and infrastructure quality, including surface conditions, number and width of lanes, and functional road classification. As demonstrated in previous studies, the use of conditional distances yields more realistic estimates of travel time in regional transport networks, particularly in predominantly rural areas.

To calculate conditional distances, the actual length of each road segment was multiplied by a coefficient corresponding to its road category: 1.0 for national roads, 1.1 for regional roads, 1.2 for territorial roads, 1.4 for oblast-level roads, and 1.5 for district roads. These coefficients, with minor modifications, were adopted from the methodology proposed in [Baiteryakov]. Travel times were then derived along the shortest paths obtained from the weighted graph, integrating both road length and assumed travel speed.

The resulting travel-time values were interpolated over the study area to produce continuous accessibility surfaces suitable for spatial comparison and cartographic visualisation. Cubic interpolation was applied to generate smoother isochrone boundaries and reduce artefacts associated with discrete network-based calculations. Isochrones were drawn at 30-minute intervals both for assessing accessibility of community centres relative to their respective district centres and for evaluating accessibility to the regional centre. This interval selection ensured a balance between analytical resolution and visual interpretability.

Isochrone maps provide an effective tool for assessing practical accessibility, enabling the identification of areas characterised by limited connectivity and potential transport disadvantage. They are particularly valuable for highlighting peripherally located communities, supporting infrastructure planning, and evaluating the spatial implications of administrative-territorial reforms on regional accessibility patterns.

All calculations and modelling procedures were conducted in the Python environment. The NetworkX library was used for graph processing and shortest-path analysis, while SciPy.interpolate.griddata supported spatial interpolation. Final visualisation of the isochrone maps was produced using Matplotlib. All analytical workflows were implemented in Google Colab, ensuring reproducibility, interactive data processing, and efficient visualisation.

FOR AUTHOR USE ONLY

2.7. Rationale & Methodological Limitations

This methodology combines quantitative network analysis with geospatial interpretation, aligning with best practices in human geography and transport planning. The methodological framework adopted in this study is grounded in the human-geographical understanding of transport accessibility as a relational spatial property, emerging from the interaction between settlement systems, transport infrastructure, and territorial organisation. By integrating graph-theoretical measures with isochrone-based accessibility assessment, the study captures both structural centrality and functional connectivity, offering a robust framework for understanding transport accessibility at the regional scale. This approach is particularly appropriate for relative

sparsely populated areas like Sumy Oblast, where network sparsity and uneven settlement distribution can amplify disparities in access to services, social opportunities, and economic centres. The choice of graph-theoretical analysis and isochrone modelling is therefore motivated by the need to capture both the structural configuration of the regional transport network and its implications for spatial integration of territorial communities.

Graph-based modelling allows transport networks to be analysed as coherent spatial systems, in which accessibility is not merely a function of distance or travel time, but also of network position, connectivity, and centrality. Centrality measures and connectivity indices make it possible to identify structurally important nodes, peripheral areas, and potential bottlenecks, providing insights into regional cohesion that cannot be obtained through purely metric approaches. Isochrone modelling, in turn, complements this perspective by translating abstract network relations into spatially interpretable travel-time zones, facilitating policy-relevant interpretation of accessibility patterns.

FOR AUTHOR USE ONLY

At the same time, the adopted methodology involves a number of conceptual and practical limitations that define the analytical scope of the study.

First, the transport network is represented as a static graph, assuming stable travel conditions and average speeds. This abstraction does not account for temporal variability in traffic intensity, seasonal changes, weather conditions, or temporary disruptions, all of which may significantly affect actual travel times, particularly in rural and peripheral areas.

Second, the use of conditional kilometres and road-category coefficients represents a methodological compromise aimed at approximating travel impedance in the absence of detailed dynamic data. While this approach improves upon purely Euclidean or unweighted network representations, it cannot fully capture local differences in road quality, maintenance status, congestion, or safety conditions. Consequently, the resulting accessibility indicators should be interpreted as relative and comparative measures, rather than precise estimates of real travel duration.

Third, the analysis focuses exclusively on automobile-based accessibility, excluding public transport, pedestrian mobility, and multimodal travel behaviour. This limitation is particularly relevant in a human-geographical context, as effective accessibility for different social groups may diverge significantly from car-based potential accessibility. However, incorporating timetable-based public transport modelling would require dynamic datasets that are often incomplete or unavailable at the regional scale.

Fourth, the study prioritises structural and topological accessibility, derived from network configuration and spatial relationships between settlements. Socio-economic variables – such as income, car ownership, demographic structure, or institutional barriers – are not directly embedded in the accessibility metrics. As a result, the analysis captures potential accessibility rather than lived or experienced mobility, which would require a complementary social-geographical or behavioural approach.

Finally, the research reflects the administrative-territorial structure established after the 2020 reform, which reshaped the spatial logic of service provision and governance in Ukraine. While this framework is analytically justified, ongoing institutional adjustments and war-related disruptions may alter transport accessibility patterns over time. The results therefore represent a context-specific snapshot rather than a fixed spatial condition.

FOR AUTHOR USE ONLY

By explicitly linking methodological choices with their limitations, this study positions graph-theoretical and isochrone-based analysis as a deliberate analytical lens rather than a universal solution. The approach is well suited for revealing structural inequalities, spatial peripherality, and patterns of regional integration, while acknowledging the need for future research that integrates dynamic mobility data, multimodal transport systems, and socio-demographic dimensions of accessibility.

* * *

In summary, the methodological framework developed for this study integrates both topological and weighted approaches to evaluate transport accessibility across Sumy

Oblast. The combination of graph-based modelling, connectivity metrics, and isochrone mapping provides a comprehensive toolkit for quantifying both structural and functional aspects of the regional transport network. Topological distance analysis offers insights into the embeddedness and relational centrality of settlements, while connectivity measures capture the cohesion, efficiency, and robustness of the network. Isochrone modelling complements these approaches by translating network structure into realistic travel-time-based accessibility zones. Together, these methods establish a rigorous, reproducible, and scalable framework for assessing transport accessibility at the regional scale, forming a robust basis for subsequent analyses of spatial centrality and network influence.

FOR AUTHOR USE ONLY

CHAPTER 3. GRAPH-TOPOLOGICAL AND CONNECTIVITY-BASED ANALYSIS OF THE TRANSPORT NETWORK

Transport accessibility is not only a function of distance or travel time, but also a structural property of spatial systems reflecting the organisation, cohesion, and hierarchy of networks. From a human geography perspective, the position of settlements within a transport network shapes everyday mobility, access to services, and the capacity of territories to sustain social and economic interactions. Before assessing effective accessibility based on travel time or transport costs, it is therefore essential to examine the underlying structural configuration of the network, which determines the range of potential connections available to different places.

This chapter assesses transport accessibility in Sumy Oblast using topological and connectivity-based approaches derived from graph theory. These methods conceptualise accessibility as a relational property defined by the arrangement of nodes and links rather than by metric characteristics. Analysis of topological distances and connectivity indices makes it possible to identify structurally central and peripheral community centres, evaluate overall network cohesion, and reveal core – periphery patterns that are not immediately evident in distance- or time-based analyses.

FOR AUTHOR USE ONLY

Topological accessibility captures the extent to which a settlement is embedded in the network through the number and configuration of its connections, reflecting the minimum number of intermediate nodes required to reach other centres. Connectivity-based measures extend this perspective by characterising network density, compactness, clustering, efficiency, and diameter, thereby providing an integrated view of how effectively the transport system supports regional integration.

In the context of administrative-territorial reform and the increasing functional role of territorial community centres, such an analysis is particularly relevant. Structural accessibility defines the potential for interaction, service provision, and mobility prior to the consideration of actual travel conditions. Accordingly, the approaches applied in this chapter should be interpreted as indicators of potential

transport accessibility, revealing the spatial logic and internal organisation of the regional transport network rather than its operational performance.

3.1. Assessment of Transport Accessibility Based on Graph Topological Distance Analysis

At the first stage of the analysis, the territorial accessibility of territorial community centres was assessed using a classical graph-based approach grounded in topological distance analysis. This method evaluates accessibility through the sum of topological distances between a given node and all other nodes in the network, thereby reflecting its relative position within the overall graph structure. In contrast to metric or time-based approaches, topological analysis captures the structural embeddedness of settlements within the transport network and enables the identification of centres that play a key role in maintaining overall network cohesion and connectivity.

The transport accessibility coefficient was calculated as the ratio of the sum of topological distances from a given centre to the total number of edges in the graph. Nodes characterised by the smallest values of the distance sum occupy the most central positions within the network, as they are separated from other centres by a smaller number of intermediate nodes. According to the results, the most central community centres are Vorozhba, Stepanivka, Sumy, Lebedyn, and Bilopillia. The sum of topological distances ranges from 187 (Vorozhba) to 420 (Seredyna-Buda), indicating a pronounced differentiation in network positions across the region and revealing a clearly expressed core – periphery structure.

FOR AUTHOR USE ONLY

A more detailed examination of the topological distance matrix shows that the most central nodes are characterised not only by low total distance values but also by relatively balanced and symmetrical distributions of distances to other centres. Vorozhba and Stepanivka, for example, maintain short topological paths to both the regional centre and peripheral communities, effectively functioning as intermediate connectors that reduce overall path lengths within the network. This confirms their role as structurally important nodes, contributing to network integration beyond their formal administrative status.

The structure of the distance matrix further indicates the presence of semi-cohesive subgroups of settlements, within which topological distances remain relatively small, whereas connections between these subgroups require a higher number of intermediate nodes. Such a configuration is typical of transport networks that evolved incrementally and reflects the combined influence of historical settlement patterns and a predominantly radial – linear road layout. In this respect, the regional network exhibits features of partial modularity, where relatively strong internal cohesion within certain areas coexists with weaker inter-module connectivity.

The transport accessibility coefficient, defined as the ratio of the sum of topological distances to the total number of graph edges, is inversely proportional to the distance sum and varies from 2.6 (Vorozhba) to 5.9 (Seredyna-Buda). For the regional centre, Sumy, this coefficient equals 2.9, indicating a high – but not dominant – level of topological centrality. This result is methodologically significant, as it suggests that Sumy's functional importance within the transport system is not solely a consequence of its administrative role but is shared with several structurally well-positioned secondary centres (Table 1).

FOR AUTHOR USE ONLY

The group of centres with the most advantageous transport-geographical positions – Vorozhba (2.6), Stepanivka (2.7), Sumy (2.9), Lebedyn and Bilopillia (both 3.0) – forms a relatively compact topological core of the regional network. These settlements are characterised by multiple alternative paths to other nodes, which enhances overall network robustness and reduces dependence on single transit corridors.

In contrast, the least accessible centres in topological terms are Hrun, Svesa (both 4.7), Znob-Novhorodske (4.8), Kyrykivka (5.3), Khutir-Mykhailivskyi (5.5), and Seredyna-Buda (5.9). These settlements occupy peripheral positions within the network and exhibit weaker structural integration. The topological distance matrix demonstrates that these nodes are separated from the network core by long chains of intermediate vertices, often with limited alternative routes, which increases their structural vulnerability and dependence on a small number of connections.

Matrix of shortest topological distances, their sums and transport accessibility coefficients of territorial community centers in Sumy Oblast

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	Sum of topological distances	Transport accessibility coefficient
1		6	1	6	2	3	5	4	3	2	2	3	5	7	8	3	6	8	6	3	4	4	2	5	1	4	2	2	2	3	3	5	5	5	4	3	5	1	7	9	2	1	4	6	1	6	7	5	6	2	7	206	2,9
2	6		7	7	6	9	4	4	9	8	4	5	6	7	9	4	7	7	7	6	3	2	8	5	4	2	5	8	8	3	9	6	7	4	5	7	1	5	8	10	3	7	8	2	7	6	5	6	6	8	7	297	4,2
3	1	7		7	3	2	5	5	2	1	3	4	6	6	9	4	7	9	5	6	5	5	1	7	2	5	3	2	1	4	2	6	4	6	5	6	6	2	8	10	3	2	3	7	2	5	3	6	7	3	8	231	3,3
4	6	7	7		4	10	3	3	9	8	8	3	1	12	3	5	2	2	12	9	4	7	8	2	7	7	6	4	8	9	9	3	11	5	2	5	6	7	2	4	8	5	10	5	7	9	8	2	1	7	1	293	4,1
5	2	6	3	4		5	3	2	5	4	4	1	3	9	7	4	4	6	8	5	3	6	4	4	3	6	2	2	4	5	5	3	7	4	3	1	5	3	5	7	4	1	6	4	3	8	4	2	4	4	5	212	3,0
6	3	9	2	10	5		7	7	2	1	5	6	8	4	11	6	9	11	3	4	7	7	1	8	5	7	5	4	2	6	2	8	2	8	7	6	8	4	10	12	6	4	1	9	4	3	4	8	8	5	10	294	4,1
7	5	4	5	3	3	7		2	8	7	6	2	2	10	5	2	3	3	10	9	1	4	7	1	7	4	3	5	8	5	8	5	8	2	9	2	1	4	3	6	4	6	5	4	10	2	6	8	8	2	2	7	3	243	3,4
8	4	4	5	3	2	7	2		7	6	6	1	2	11	5	2	3	4	10	7	1	4	6	2	5	4	3	4	6	5	7	2	9	2	1	3	3	5	4	6	5	3	8	2	5	7	6	2	3	6	4	224	3,2
9	3	9	2	9	5	2	8	7		3	6	6	8	4	11	6	9	10	1	4	7	8	1	8	5	7	5	4	2	7	4	8	2	8	7	6	8	4	10	12	6	4	4	9	4	3	4	8	9	5	10	302	4,3
10	2	8	1	8	4	1	7	6	3		4	5	7	5	10	5	7	9	4	5	6	6	2	7	3	6	4	3	2	5	1	7	3	7	6	5	7	3	8	11	4	3	2	8	3	4	5	7	8	4	9	260	3,7
11	2	4	3	8	4	5	6	6	6	4		5	7	4	10	6	8	8	5	3	5	5	2	4	7	1	2	4	3	4	1	5	7	4	6	6	5	3	1	9	11	2	3	6	4	3	3	2	7	8	4	8	244	3,4
12	3	5	4	3	1	6	2	1	6	5	5		2	6	5	3	3	3	4	8	5	3	5	4	2	3	5	3	3	4	5	5	2	3	3	1	2	4	3	4	6	4	2	6	3	3	5	4	2	3	4	4	187	2,6
13	5	6	6	1	3	8	2	2	8	7	7	2		9	3	4	1	3	11	8	3	6	7	1	5	6	5	5	7	7	8	2	10	4	1	4	5	6	2	4	7	3	9	4	6	11	7	1	2	7	2	253	3,6
14	7	7	6	12	9	4	10	11	4	5	4	6	9		12	7	10	11	3	1	7	6	5	9	3	5	6	5	6	5	6	9	2	8	8	7	6	5	11	13	4	5	3	7	5	1	2	9	10	6	11	333	4,7
15	8	9	9	3	7	11	5	5	11	10	10	5	3	12		7	2	1	14	11	7	9	10	4	9	9	8	8	10	10	12	12	13	8	5	8	8	9	1	1	11	8	12	7	10	11	10	4	3	11	2	393	5,5
16	3	4	4	5	4	6	2	2	6	5	6	3	4	7	7		4	5	9	6	1	4	5	3	4	4	1	3	5	5	6	3	7	2	2	5	3	4	5	6	5	2	7	2	4	6	5	3	4	5	5	218	3,1
17	6	7	7	2	4	9	3	3	9	7	8	3	1	10	2	4		3	12	4	4	7	8	2	7	7	6	6	8	8	9	3	11	5	2	2	6	7	1	3	8	5	10	5	7	12	8	2	3	8	2	286	4,0
18	8	7	9	2	6	11	3	4	10	9	8	4	3	11	1	5	3		14	11	4	7	10	2	9	7	8	8	10	8	11	6	13	5	4	7	6	9	2	1	8	7	12	5	9	11	10	4	1	10	1	344	4,8
19	6	7	5	12	8	3	10	10	1	4	5	8	11	3	14	9	12	14		4	9	2	4	11	4	6	8	7	3	6	5	11	1	10	10	9	7	7	14	15	5	7	2	8	7	2	3	11	12	8	13	373	5,3
20	3	6	6	9	5	4	9	7	4	5	3	5	8	1	11	6	4	11	4		7	5	5	8	2	4	5	4	6	4	6	8	2	8	7	6	5	4	10	12	3	3	3	6	4	1	1	8	9	5	10	282	4,0
21	4	3	5	4	3	7	1	1	7	6	5	3	3	7	7	1	4	4	9	7		3	6	2	5	3	2	4	6	4	7	3	8	1	5	4	2	5	5	7	4	3	8	1	5	7	6	3	3	6	4	223	3,1
22	4	2	5	7	6	7	4	4	8	6	2	5	6	6	9	4	7	7	2	5	3		6	5	3	2	5	5	6	1	7	6	6	4	5	7	1	3	8	9	3	5	7	2	5	5	4	6	6	6	7	254	3,6
23	2	8	1	8	4	1	7	6	1	2	4	4	7	5	10	5	8	10	4	5	6	6		7	3	5	4	3	1	5	2	7	3	7	6	5	7	3	10	11	4	3	2	7	5	4	5	7	8	4	9	261	3,7
24	5	5	7	2	3	8	1	2	8	7	7	2	1	9	4	3	2	2	11	8	2	5	7		7	5	4	5	7	6	8	3	10	3	1	4	4	6	3	5	6	4	9	3	6	9	8	2	1	7	2	249	3,5
25	1	4	2	7	3	5	7	5	5	3	1	3	5	3	9	5	7	9	4	2	5	3	3	7		2	3	2	3	2	4	6	3	6	5	4	3	2	8	10	1	2	4	4	2	2	1	6	7	3	8	211	3,0
26	4	2	5	7	6	7	4	4	7	6	2	5	6	5	9	4	7	7	6	4	3	2	5	5	2		6	5	6	4	7	6	5	4	5	7	1	3	8	10	1	5	6	2	5	4	3	6	6	6	7	249	3,5
27	2	5	3	6	2	5	3	3	5	4	4	3	5	6	8	1	6	8	8	5	2	5	4	4	3	6		2	4	5	5	5	6	3	4	3	4	3	7	9	4	1	6	3	3	5	4	5	6	4	7	224	3,2
28	2	8	2	4	2	4	5	4	4	3	3	3	5	5	8	3	6	8	7	4	4	5	3	5	2	5	2		3	4	4	5	6	5	4	3	6	2	7	9	3	1	5	5	2	4	3	5	6	3	7	218	3,1
29	2	8	1	8	4	2	8	6	2	2	4	4	7	6	10	5	8	10	3	6	6	6	1	7	3	6	4	3		5	2	7	5	7	6	5	7	3	9	11	4	2	4	7	3	5	4	7	8	4	9	266	3,7
30	3	3	4	9	5	6	5	5	7	5	1	5	7	5	10	5	8	8	6	4	4	1	5	6	2	1	5	4	5		6	8	5	5	7	6	2	2	9	11	2	4	6	3	4	4	3	8	7	5	8	259	3,6
31	3	9	2	9	5	2	8	7	4	1	5	5	8	6	12	6	9	11	5	6	7	7	2	8	4	7	5	4	2	6		8	3	8	7	6	8	4	11	12	4	3	2	9	3	4	4	8	10	5	9	303	4,3
32	5	6	6	3	3	8	2	2	8	7	7	2	2	9	12	3	3	6	11	8	3	6	7	3	6	6	5	5	7	8	8		10	4	2	4	5	6	4	6	7	4	9	4	6	8	7	3	4	7	4	281	4,0
33	5	7	4	11	7	2	9	9	2	3	4	3	10	2	13	7	11	13	1	2	8	6	3	10	3	5	6	5	5	5	3	10		9	9	8	6	6	12	14	4	1	1	7	6	1	2	10	11	7	12	320	4,5
34	5	4	6	5	4	8	2	2	8	7	6	3	4	8	8	2	5	5	10	8	1	4	7	3	6	4	3	4	7	5	8	4	9		3	3	3	6	6	8	5	4	9	2	7	8	7	4	4	7	5	266	3,7
35	4	5	5	2	3	7	1	1	7	6	6	1	1	8	5	2	2	4	10	7	2	5	6	1	5	5	4	5	6	7	7	1	9	3		3	4	5	4	6	6	3	8	3	5	7	6	1	2	6	3	225	3,2
36	3	7	6	5	1	6	4	3	6	5	5	2	4	7	8	5	2	7	9	6	4	7	5	4	4	7	3	3	5	6	6	4	8	3	3		6	4	6	8	5	2	7	5	4	5	5	4	5	5	6	250	3,5
37	5	1	6	6	5	8	3	3	8	7	3	4	5	6	8	3	6	6	7	5	2	1	7	4	3	1	4	6	7	2	8	5	6	3	4	6		4	7	8	2	9	9	1	6	5	4	5	5	7	6	252	3,5
38	1	5	2	7	3	4	6	5	4	3	1	3	6	5	9	4	7	9	7	4	5	3	3	6	2	3	3	2	3	4	6	6	6	5	4	4	4		7	9	3	2	5	5	2	4	3	6	7	3	8	226	3,2
39	7	8	8	2	5	10	4	4	10	8	9	4	2	11	1	5	1	2	14	10	5	8	10	3	8	8	7	7	9	9	11	4	12	6	4	6	7	7		2	10	6	11	6	8	10	9	3	2	9	1	333	4,7
40	9	10	10	4	7	12	6	6	12	11	11	11	6	4	13	1	6	3	1	15	12	7	9	11	5	10	10	9	9	11	11	12	6	14	8	6	8	8	9	2		11	8	13	8	10	12	11	5	4	11	3	420	5,9
41	2	3	3	8	4	6	5	5	6	4	2	4	7	4	11	5	8	8	5	3	4	3	4	6	1	1	4	3	4	2	4	7	4	5	6	5	2	3	10	11		3	5	3	3	3	2	7	7	4	8	237	3,3
42	1	7	2	5	1	4	4	3	4	3	3	2	3	5	8	2	5	7	7	3	3	5	3	4	2	5	1	1	2	4	3	4	1	4	3	2	9	2	6	8	3		5	4	2	4	3	4	3	5	3	6	190	2,7
43	4	8	3	10	6	1	10	8	4	2	6	6	9	3	12	7	10	12	2	3	8	7	2	9	4	6	6	5	4	6	2	9	1	9	8	7	9	5	11	13	5	5		9	5	2	3	9	10	6	11	322	4,5
44	6	2	7	5	4	9	2	2	9	8	4	3	4	7	7	2	5	5	8	6	1	2	7	3	4	2	3	5	7	3	9	4	7	2	3	5	1	5	6	8	3	4	9		7	6	5	4	4	8	5	247	3,5
45	1	7	2	7	3	4	6	5	4	3	3	3	6	5	10	4	7	9	7	4	5	5	3	6	2	5	3	2	3	4	3	6	6	7	5	4	6	6	8	10	3	2	5	7		4	3	6	7	1	8	245	3,5
46	6	6	5	9	8	3	8	7	3	4	3	5	11	1	11	6	12	11	2	1	7	5	4	9	2	4	5	4	5	4	4	8	1	8	7	5	5	4	10	12	3	4	2	6	4		1	8	9	5	10	287	4,0
47	7	5	3	8	4	4	8	6	4	5	2	4	7	2	10	5	8	10	3	1	6	4	5	8	1	3	4	3	4	3	4	7	2	7	6	5	4	3	9	11	2	3	3	5	3	1		7	8	4	9	250	3,5
48	5	6	6	2	2	8	2	2	8	7	7	2	1	9	4	3	2	4	11	8	3	6	7	2	6	6	5	5	7	8	8	2	10	4	1	4	5	6	3	5	7	4	9	4	6	8	7		3	7	3	260	3,7
49	6	6	7	1	4	8	2	3	9	8	8	3	2	10	3	4	3	1	12	9	3	6	8	1	7	6	6	6	8	7	10	4	11	4	2	5	5	7	2	4	7	5	10	4	7	9	8	3		10	1	285	4,0
50	2	8	3	7	4	5	7	6	5	4	4	4	7	6	11	5	8	10	8	5	6	6	4	7	3	6	4	3	4	5	5	7	7	7	6	5	7	3	9	11	4	3	6	8	1	5	4	7	10		9	291	4,1
51	7	7	8	1	5	10	3	4	10	9	8	4	2	11	2	5	2	1	13	10	4	7	9	2	8	7	7	7	9	8	9	4	12	5	3	6	6	8	1	3	8	6	11	5	8	10	9	3	1	9		317	4,5

Note: Node numbers correspond to the settlement names shown in Figure 1.

Electronic Archive Library

At the same time, several nodes display a structurally important intermediary role, even though their absolute centrality indicators are not among the lowest. These centres function as topological bridges, reducing distances between otherwise weakly connected parts of the network. Their removal or degradation would result in a disproportionate increase in overall path lengths, underscoring their critical importance for network stability. This property is particularly evident in settlements located at the intersections of radial and transversal routes, which mediate flows between the core and peripheral zones.

The topological distance matrix also reveals a marked asymmetry in accessibility between the core and the periphery. While central nodes maintain relatively short and evenly distributed distances to most other centres, peripheral settlements tend to have long distances not only to the core but also to one another. This generates a cumulative isolation effect, whereby peripheral centres remain topologically distant from both the regional core and neighbouring peripheries, reinforcing their marginal position within the network.

FOR AUTHOR USE ONLY

From an administrative and spatial planning perspective, these findings are particularly relevant in the context of the administrative-territorial reform implemented in 2020. The consolidation of territorial communities and the redefinition of service provision areas increased the functional importance of district and community centres. However, the topological analysis demonstrates that not all newly designated centres occupy structurally favourable positions within the transport network. In several cases, administrative status does not coincide with topological centrality, potentially creating spatial mismatches between governance responsibilities and actual accessibility conditions.

Moreover, the matrix highlights that topological proximity does not necessarily imply geographical proximity, especially in areas where the road network follows indirect routes constrained by natural features or historical development. This distinction reinforces the need to differentiate between structural accessibility, as captured by topological metrics, and effective accessibility, which depends on distance, travel time, and transport conditions.

Beyond aggregate indicators, the topological distance matrix provides valuable insights into the internal organisation and hierarchical structure of the regional transport network. Notably, the spatial distribution of topologically peripheral centres is not random but reveals a clear gradient from a compact central core to elongated peripheral branches. Most of these centres are located along the northern and north-eastern margins of Sumy Oblast, where settlement density is lower and the transport network assumes a more linear, dendritic configuration. In such areas, distance distributions are highly uneven, resulting in elongated topological paths and limited redundancy. This gradient manifests itself in a gradual increase in average pairwise distances when moving from the central part of the oblast towards its marginal zones, particularly in the north and north-east, reinforcing peripheralization processes from a network perspective.

Despite its analytical clarity, this approach has important methodological limitations. Its primary shortcoming lies in the fact that it does not account for real geographical distances, travel time, or transport costs. In real transport systems, nodes with an identical number of topological connections may differ substantially in terms of physical accessibility due to distance, road quality, or speed constraints. Consequently, topological centrality does not necessarily translate into effective accessibility.

FOR AUTHOR USE ONLY

Furthermore, the method does not adequately capture the functional significance of critical infrastructural elements, such as key transit corridors, bridges, or junctions, whose disruption could disproportionately affect overall network performance. From a human-geographical perspective, this limits the ability of purely topological analysis to reflect everyday mobility practices, service accessibility, and socio-economic interactions.

Finally, the use of the total number of edges as a normalising parameter constrains the applicability of the method for comparative analysis across graphs with differing densities or structural characteristics, such as interregional or national-scale networks.

Consequently, while topological distance analysis provides an important first approximation of spatial centrality and reveals the structural logic of the regional transport network, it should be interpreted as an indicator of potential accessibility rather than a direct representation of real transport conditions. This justifies the subsequent application of weighted graph metrics and travel-time-based isochrone modelling, which incorporate distance, speed, and infrastructural hierarchy and are discussed in the following sections.

Taken together, the interpretation of the topological distance matrix confirms that the transport network of Sumy Oblast is characterised by a pronounced core – periphery structure, limited redundancy in peripheral areas, and the presence of a small number of structurally critical nodes that sustain overall connectivity. These characteristics explain the observed differentiation in accessibility indicators and substantiate the transition to weighted and time-based analyses, which enable a more realistic assessment of transport accessibility and regional cohesion.

FOR AUTHOR USE ONLY

3.2. Assessment of Transport Accessibility Based on Graph Connectivity Measures

The methodology for assessing transport accessibility based on graph connectivity measures offers significant advantages over purely topological approaches, as it allows consideration not only of the number of connections between nodes but also of the overall network structure, its cohesion, and its functional efficiency. By employing parameters such as average shortest path length, clustering coefficient, graph density, network efficiency, and diameter, this approach provides a deeper understanding of transport connectedness and enables an assessment of how effectively the network supports regional accessibility.

Unlike the topological method, which is limited to a simplified ratio of the sum of topological distances to the number of edges, the connectivity-based approach makes it possible not only to estimate the general level of accessibility but also to identify structural weaknesses within the network, including isolated, weakly integrated, or excessively loaded nodes. This makes it more suitable for the analysis of

real-world transport systems and for supporting decision-making in infrastructure planning and regional development.

Based on calculations performed in the Python environment using the NetworkX library, the key connectivity characteristics of the graph modelling the transport network of Sumy Oblast were determined.

Graph density (D) reflects how close a given transport network graph is to a complete graph, in which all possible nodes are connected by edges (D = 100%). Graphs with low density (below 10%) are typically characterised by weak direct connectivity between nodes. In the present case, the graph density equals 0.0580 (5.8%), indicating that the network is highly sparse. At the same time, such density values are typical of real transport networks in regions such as Sumy Oblast, where most nodes are connected indirectly through intermediary settlements rather than via direct links.

The *average shortest path length* – defined as the mean number of steps required to move from one territorial community centre to another along the shortest available route – equals 4.67. This indicates that an average journey within the transport system requires passing through approximately four to five intermediate nodes. Such a value suggests a relatively compact network structure with satisfactory connectivity between centres. The network is neither excessively fragmented nor characterised by uniformly short routes between all nodes.

FOR AUTHOR USE ONLY

At first glance, a certain contradiction emerges: despite the high sparsity of the graph, the average shortest path length remains relatively low. This indicates an efficient organisation of connections within the network. In our view, this pattern is explained by the presence of several key nodes with high connectivity (for example, nodes 1 and 35), which function as transport hubs. Through these central nodes, the graph remains well connected, even in the absence of dense direct links. Since all nodes belong to a single connected component, the absence of isolated subgraphs ensures a relatively even level of accessibility across the entire transport system.

In addition, the presence of several "long-range" connections between selected nodes contributes to reducing the average path length. These links function as transport

"express corridors", reducing the number of intermediate steps between distant centres and creating favourable conditions for efficient movement across the network. Thus, even with low density, the transport network of Sumy Oblast maintains a relatively high degree of compactness due to its underlying topology.

To further examine the internal cohesion of the network, the *average clustering coefficient* was calculated. This metric assesses the tendency of nodes to form local clusters or triads and represents the probability that two neighbours of a given node are also directly connected to each other. In other words, it characterises the level of local interconnectedness within the graph.

For the transport network of Sumy Oblast, the average clustering coefficient equals 0.17, which is relatively low. This indicates a limited degree of local integration and suggests that the network contains only a small number of tightly connected local communities. Instead, the network is dominated by a hierarchical structure with a substantial proportion of transit nodes, rather than by a clustered topology typical of dense urban street networks. Such a configuration reflects the predominance of regional and territorial roads with a limited number of alternative routes connecting community centres.

FOR AUTHOR USE ONLY

At the same time, several areas of increased connection density can be identified within the graph, allowing the delineation of local clusters.

Cluster 1 includes the city of Sumy and the centres of adjacent communities (nodes 1, 10, 11, 25, 38, 42, 45, 50), forming a dense network of connections in the eastern part of the oblast. Node 1 (Sumy) exhibits the highest degree centrality (0.18) and a high betweenness centrality (0.57), confirming its role in maintaining connectivity between this cluster and the rest of the transport network.

Cluster 2 is located in the western part of the oblast (nodes 7, 16, 21, 24, 34) and is characterised by dense internal connections. Node 21 (Konotop) functions as the central node of this cluster.

Cluster 3 comprises nodes with a high level of interaction in the central part of the oblast (nodes 4, 13, 17, 24, 35, 48, 51). Within this cluster, node 35 (Putyvl) is particularly important (degree centrality 0.14), as it connects the internal nodes of the

cluster with other parts of the transport network and can be regarded as a local transport hub.

Cluster 4 is located in the southern part of the region (nodes 19, 20, 33, 43, 46, 47). Nodes within this cluster are strongly interconnected and form a peripheral segment of the graph.

The most connected area of the network is Cluster 1 (Sumy cluster), which contains node 1 as the principal transport hub. The Putyvl cluster (Cluster 3) is characterised by high internal connectivity but remains relatively isolated from other parts of the network. Clusters 2 and 4 correspond to peripheral zones where local connectivity is more developed than global connectivity.

The *graph diameter* is an important indicator of global network connectivity, as it reflects the maximum distance between the most remote nodes in the system. For the transport network of Sumy Oblast, the diameter equals 11, meaning that the longest shortest path between any two community centres consists of 11 steps (edges). In the context of sparse graphs with moderate compactness, such a value can be considered moderate and supports the conclusions drawn from the density (5.8%) and average shortest path length (4.67) analyses.

FOR AUTHOR USE ONLY

Despite the overall sparsity of the network, the presence of several "mainline" connections helps to keep the diameter within acceptable limits. Compared with other transport networks, a diameter of 11 can be regarded as relatively large, particularly in the context of efficiently organised infrastructures, where the presence of high-speed corridors and major hubs often reduces the diameter to values of 5-8 even in large networks [(e.g. Watts)]. In this case, the diameter value indicates a moderate remoteness of certain nodes and suggests that some sections of the network may suffer from limited connectivity or a lack of alternative routes.

Graph efficiency represents a measure based on the inverse of shortest path lengths between all pairs of nodes and serves as an indicator of how "convenient" or "fast" accessibility can be ensured within the network. The shorter the distance between two nodes, the greater their contribution to overall efficiency. For the transport network of Sumy Oblast, the calculated efficiency value of 0.29 indicates that, on

average, transport accessibility between nodes is ensured, but remains constrained by relatively large shortest path distances for many node pairs. Community centres are spatially distant from one another, and connections between them are rarely direct.

As a summary of the key connectivity metrics and local network structures described above, Table 2 presents the principal indicators characterising the transport network graph of Sumy Oblast. These metrics provide a concise overview of both global network properties and locally clustered regions, highlighting areas of high cohesion and peripheralisation within the regional transport system.

Table 2

Key metrics characterising the connectivity of the Sumy Oblast transport network graph

Indicator	Value	Comment
Graph density (D)	5.8%	The graph is sparse, which is typical for regional transport networks.
Average shortest path length	4.67	Indicates a relatively efficient organisation of connections between nodes.
Clustering coefficient	0.17	Low level of local connectivity, suggesting a hierarchical network structure.
Graph diameter	11	Moderate separation between the most isolated points in the network.
Graph efficiency	0.29	Node accessibility is sufficient but limited due to large distances between some points.
Cluster 1 (Sumy)	Nodes: 1, 10, 11, 25, 38, 42, 45, 50	The most connected region, with node 1 serving as the main hub.
Cluster 2 (Western)	Nodes: 7, 16, 21, 24, 34	Dense connections in the western part of the oblast, with node 21 as the central node.
Cluster 3 (Central)	Nodes: 4, 13, 17, 24, 35, 48, 51	High connectivity density, with node 35 as the central node.
Cluster 4 (Southern)	Nodes: 19, 20, 33, 43, 46, 47	Peripheral part of the graph with dense local connections.

Note: Node numbers correspond to the settlement names shown in Figure 1.

IRBAUTHORS.COM

Despite its analytical advantages, the connectivity-based approach to assessing transport accessibility also has significant limitations that may reduce its effectiveness when applied to real transport systems. In particular, connectivity indicators do not always adequately reflect the functional role of individual nodes within the network. For example, the clustering coefficient effectively captures local interconnectedness but does not allow assessment of a node's strategic importance for maintaining overall network connectivity. This is especially relevant in transport network analysis, where

certain nodes may play a critical role in regional mobility despite having low local connectivity.

In addition, the methodology is sensitive to structural changes in the graph: even minor modifications, such as the addition or removal of a single edge, can substantially affect parameters such as graph diameter or average shortest path length.

Thus, while connectivity-based assessment provides an effective tool for general analysis of transport networks, its application under real-world conditions requires consideration of additional factors. The most appropriate strategy is to combine this approach with methods that incorporate centrality indices and real transport costs. Such an integrated framework enables a more comprehensive and objective assessment of regional accessibility and supports the optimisation of transport infrastructure.

* * *

FOR AUTHOR USE ONLY

In summary, Chapter 3 demonstrates that the assessment of transport accessibility in Sumy Oblast benefits from a dual approach: topological distance analysis provides a foundational understanding of the network's structural logic, revealing the core – periphery configuration, semi-cohesive clusters, and critical intermediary nodes, while connectivity-based metrics offer deeper insights into network cohesion, efficiency, and local clustering. Together, these analyses elucidate how the regional transport system is organised, highlighting both the compactness and sparsity of the network, the relative centrality of key hubs, and the peripheralisation of certain community centres. The findings underscore that while administrative status often correlates with network importance, several structurally central nodes emerge as critical for maintaining regional connectivity, independent of formal governance. These insights provide a robust basis for the subsequent integration of weighted and time-based analyses, enabling a more realistic and policy-relevant assessment of mobility, accessibility, and regional cohesion.

CHAPTER 4. TRANSPORT ACCESSIBILITY ANALYSIS BASED ON GRAPH CENTRALITY MEASURES

Building on the findings from the topological and connectivity-based assessments, we focuses on the evaluation of transport accessibility using graph centrality measures, which provide a node-level perspective on the relative importance and influence of settlements within the network. This analysis employs a set of complementary metrics, including the Bavelas and Beauchamp indexes, degree, closeness, betweenness, and eigenvector centrality as introduced in Section 2.5. Each metric captures a distinct aspect of nodal significance, ranging from relative accessibility and structural positioning to the capacity to mediate flows and the influence of connected neighbours. By applying these measures to the Sumy Oblast transport network, the chapter aims to identify critical nodes, evaluate their functional roles, and provide a more nuanced understanding of spatial hierarchies and regional cohesion. This centrality-focused analysis complements the preceding topological and connectivity evaluations, bridging network structure with practical implications for mobility, planning, and infrastructure prioritisation.

FOR AUTHOR USE ONLY

4.1. Centrality and Transport Accessibility of District Centres

For a general topological assessment of road transport accessibility of district centres in Sumy Oblast, a graph representing their transport-geographical position was constructed. This graph reflects the relative spatial arrangement of administrative centres and their mutual neighbourhood relations within the regional transport network. Following the administrative-territorial reform implemented in July 2020, five administrative districts were established in the region, replacing the previous eighteen. Consequently, the centres of these districts were represented as vertices of the corresponding graph.

As noted in the Methodology section, the assessment of transport accessibility considered not only the number and configuration of graph edges but also their weights, expressed as distances between vertices adjusted to reflect travel conditions.

At the initial stage, the *absolute accessibility index* of each graph vertex – representing a district centre – was calculated. This index characterises the sum of all graph edges (paths) connecting a given centre with all other district centres in the oblast. According to this measure, centres with the lowest index values occupy the most favourable positions. The calculations show that, in terms of the number of edges, the smallest absolute accessibility index (4) is observed for the regional centre, Sumy. A value of 7 was obtained for Shostka, while Romny and Konotop each have an index of 5, and Okhtyrka has a value of 6.

However, when accessibility is calculated using distance-based weights that account for travel conditions, the results differ substantially. Sumy retains its most central position, with a total distance of 510.1 conditional kilometres. Romny and Konotop follow, with values of 524.8 and 593.3 conditional kilometres, respectively. The least favourable position is no longer occupied by Shostka (753.8 conditional kilometres) but by Okhtyrka (812.0 conditional kilometres). In other words, a noticeable discrepancy emerges between calculations based on the number of graph edges and those based on weighted distances (Table 3).

FOR AUTHOR USE ONLY

Table 3

Transport accessibility indicators of district centres in Sumy Oblast

District centre	Absolute transport accessibility index (cond. km)	Eccentricity (cond. km)	Average node distance (cond. km)	Node centrality (Bavelas index)	Beauchamp index
Konotop	593.3	282.0	148.33	5.87	0.0067
Okhtyrka	812.0	282.0	203.00	4.13	0.0049
Romny	524.8	175.2	131.20	5.80	0.0076
Sumy	510.1	199.1	127.53	5.97	0.0078
Shostka	753.8	275.9	188.45	4.04	0.0053

To further assess transport accessibility, the *König number* and the *maximum transport remoteness (eccentricity)* of each district centre (graph vertex) were calculated. The König number, also referred to as the graph radius, represents the smallest eccentricity among all vertices; in other words, it is the minimum number of vertices through which all graph edges are connected. Centres with lower values are

considered more central. In terms of the number of edges, the König number for Sumy equals 1, while for all other district centres it is identical and equals 2.

Eccentricity for each district centre is defined as the longest shortest path from that centre to any other centre in the network. Lower values indicate more central nodes – those located closer to all others. When calculated using distance-based weights, clear differentiation becomes apparent. Romny exhibits the smallest eccentricity value (175.2 km), indicating that, among all district centres, it is closest to its most distant counterpart and therefore demonstrates the best transport accessibility within the network. Sumy (199.1 km) also shows a relatively low value, which is consistent with its role as the regional administrative centre. Konotop, Okhtyrka, and Shostka display substantially higher eccentricity values (275-282 km), indicating greater transport remoteness at the regional scale.

To assess the compactness of the district-centre graph, the *average distance* from a given node to all other nodes was calculated. The average distance between all pairs of district centres in the graph equals 159.7 km. For individual nodes, the values are as follows: Sumy – 127.53 km, Romny – 131.20 km, Okhtyrka – 203.00 km, Konotop – 148.33 km, and Shostka – 188.45 km (Table 3).

FOR AUTHOR USE ONLY

An important indicator of transport accessibility that reflects the hierarchical status of settlements is their accessibility to the administrative centre of the territory – in this case, the regional centre. Such accessibility determines the population's ability to access higher-order medical, educational, social, and other services. For district centres of Sumy Oblast, accessibility to the regional centre ranges from 78.9 to 199.1 conditional kilometres. The more than 2.5-fold variation of this indicator is explained by the large territorial extent of the oblast and the location of the regional and district centres closer to its periphery.

The best accessibility to the regional centre is observed for Okhtyrka (78.9 conditional kilometres). Intermediate values are characteristic of Romny (103.0 km) and Konotop (129.1 km), while Shostka appears to be the most remote (199.1 km). As shown by most absolute indicators of road transport accessibility, Sumy and Romny

demonstrate the most favourable positions, Konotop occupies an intermediate position, and the least favourable conditions are observed for Shostka and Okhtyrka.

As follows from Equation (7), the *Bavelas index* is calculated as the ratio of the sum of all absolute accessibility indices to the absolute accessibility index of a specific district centre. In its simplest interpretation, this index evaluates how short the shortest paths are between one centre and all others in the transport network. Higher values indicate a more favourable transport-geographical position. The obtained values (Table 3) show how "close" each district centre is to all others. The higher the Bavelas index, the more central the vertex is in terms of accessibility. The average value of this index for the analysed graph equals 5.16, indicating an overall moderate level of accessibility within the network.

The highest Bavelas index values are observed for Sumy (5.97) and Konotop (5.87), which indicates their central positions within the graph structure and relatively low cumulative distances to other cities. The lowest values are recorded for Shostka (4.04) and Okhtyrka (4.13), reflecting their relative remoteness from other district centres.

FOR AUTHOR USE ONLY

The *relative Beauchamp index* represents the ratio of the total number of nodes in the transport network to the absolute accessibility index of a given node and evaluates its relative centrality within the entire network. Unlike the Bavelas index, this measure allows the length of transport paths from a given node to be assessed not in relation to distance but in relation to network saturation. At the same time, unlike the König number – which captures only the most distant connection – the Beauchamp index incorporates the entire network structure. A higher value indicates a more favourable transport position.

The average Beauchamp index value for the analysed graph equals 0.0068. The highest values are observed for Sumy (0.0078) and Konotop (0.0077), once again confirming their relatively high transport accessibility. The lowest values are recorded for Shostka (0.0053) and Okhtyrka (0.0054), indicating their peripheral positions within the transport network structure.

Overall, the obtained index values indicate a moderate level of transport accessibility of district centres in Sumy Oblast. These values are not particularly high, suggesting potential logistical challenges in intercity connectivity, but they are not critically low either, which is supported by the sufficient level of network connectedness. Compared with transport networks of metropolitan areas or highly developed European regions, these indicators appear low. However, considering that Sumy Oblast is a peripheral region with a medium-density road network, the observed values can be regarded as typical and structurally consistent with its regional characteristics.

Importantly, the analysis demonstrates that administrative status does not automatically correspond to optimal transport centrality. Instead, centrality emerges as a relational property shaped by network configuration, distance structure, and historical development patterns.

Generally speaking, the centrality-based analysis confirms that Sumy and Romny occupy the most favourable positions in terms of transport accessibility, while Shostka and Okhtyrka exhibit pronounced peripheral characteristics. This differentiation provides an essential foundation for the subsequent sections, which further examine weighted centrality measures and their implications for regional mobility, spatial integration, and transport planning.

FOR AUTHOR USE ONLY

4.2. Analysis of Transport Accessibility Based on Graph Centrality Measures

Considering the limitations of the previously applied methodologies, the next stage of the study focuses on the analysis of transport accessibility using graph centrality measures. Unlike purely topological or aggregate accessibility indicators, graph centrality metrics take into account not only the structural properties of the network but also its weighted characteristics. This makes it possible to incorporate both physical distances and the functional significance of individual nodes within the transport system. As a result, centrality-based analysis provides a more realistic representation of transport accessibility, as it relies on actual shortest paths between nodes and captures the differentiated roles played by settlements within the network.

Graph centrality measures allow for a more precise assessment of transport accessibility by evaluating not only how accessible a given node is, but also how central it is within the overall structure of the transport network. This distinction is particularly important from the perspective of transport planning and regional development, as nodes with high centrality often perform critical functions in maintaining connectivity, redistributing flows, and ensuring network resilience. Although the calculation of centrality measures involves higher computational complexity compared to simpler topological approaches, this methodology enables the identification of key transport nodes and highlights areas with relatively favourable or unfavourable accessibility conditions. Compared to earlier methods, the use of graph centralities is therefore more robust and flexible when applied to real transport networks, and the resulting indicators have greater analytical value for evidence-based decision-making in transport and spatial planning.

FOR AUTHOR USE ONLY

In general, node centrality reflects the relative importance of individual nodes within a transport network. Different centrality measures capture different dimensions of this importance, ranging from local connectivity to global influence on network structure and flow. In this section, particular attention is first paid to degree centrality as the most intuitive indicator of local network integration.

4.2.1. Degree centrality $C_D(v)$ is a metric that determines the importance of a node based on the number of its direct connections to neighbouring nodes. In the context of a transport network, a high degree centrality indicates that a settlement is directly connected to a large number of other centres, which enhances its local accessibility and increases its role as a connector within the system. The highest values of degree centrality in the transport network of Sumy Oblast are observed for Sumy (0.18), which has the largest number of direct connections in the graph, followed by Putyvl (0.14) and Konotop (0.12). These centres play a key role in maintaining the overall connectivity of the regional transport system.

High degree centrality values for these nodes indicate their function as primary transport hubs, concentrating multiple routes and facilitating the redistribution of transport flows across the oblast. Together with Vorozhba (node 13), these centres

perform a critical role in sustaining the continuity of the transport network and ensuring alternative routing options between different parts of the region. Their structural importance is particularly evident in a relatively sparse network, where the loss or degradation of a small number of highly connected nodes could lead to a disproportionate decline in overall connectivity.

In addition to the most prominent hubs, several other nodes – such as nodes 24, 49, 51, and a number of others – also exhibit elevated degree centrality values and function as key connection points within specific regional sub-networks. While their influence is more localised, these nodes contribute significantly to intra-regional accessibility and help maintain cohesion within peripheral parts of the transport system. The spatial distribution of nodes with higher degree centrality thus reflects a hierarchical structure of the network, combining a limited number of dominant hubs with a set of secondary connectors that support regional-level integration.

The results of the degree centrality analysis for the centres of territorial communities in Sumy Oblast are summarised in Table 4.

FOR AUTHOR USE ONLY

Table 4

Degree centrality values of Sumy Oblast transport network nodes

Ordered by node ID		Ordered by descending centrality	
Node ID	**Degree centrality**	**Node ID**	**Degree centrality**
1	0.18	1	0.18
2	0.02	35	0.14
3	0.06	21	0.12
4	0.06	13	0.10
5	0.06	18	0.08
6	0.06	23	0.08
7	0.04	24	0.08
8	0.06	37	0.08
9	0.06	46	0.08
10	0.06	49	0.08
11	0.04	51	0.08
12	0.06	3	0.06
13	0.10	4	0.06
14	0.04	5	0.06
15	0.06	6	0.06
16	0.04	8	0.06
17	0.04	9	0.06
18	0.08	10	0.06
19	0.04	12	0.06
20	0.06	15	0.06

Ordered by node ID		Ordered by descending centrality	
Node ID	Degree centrality	Node ID	Degree centrality
21	0.12	20	0.06
22	0.04	25	0.06
23	0.08	26	0.06
24	0.08	30	0.06
25	0.06	33	0.06
26	0.06	39	0.06
27	0.04	43	0.06
28	0.02	47	0.06
29	0.04	7	0.04
30	0.06	11	0.04
31	0.02	14	0.04
32	0.02	16	0.04
33	0.06	17	0.04
34	0.02	19	0.04
35	0.14	22	0.04
36	0.02	27	0.04
37	0.08	29	0.04
38	0.02	40	0.04
39	0.06	41	0.04
40	0.04	42	0.04
41	0.04	44	0.04
42	0.04	45	0.04
43	0.06	48	0.04
44	0.04	2	0.02
45	0.04	28	0.02
46	0.08	31	0.02
47	0.06	32	0.02
48	0.04	34	0.02
49	0.08	36	0.02
50	0.02	38	0.02
51	0.08	50	0.02

Note: Node numbers correspond to the settlement names shown in Figure 1.

FOR AUTHOR USE ONLY

A detailed analysis of degree centrality values reveals a clearly differentiated and hierarchical structure of the transport network of Sumy Oblast. All values are normalised to the [0-1] interval, which ensures their comparability across nodes of the network. The resulting distribution is distinctly right-skewed, indicating a strong imbalance between a small number of highly connected nodes and a large group of weakly connected ones. Such a configuration is characteristic of regional transport systems dominated by a limited number of hubs embedded within a broadly dispersed settlement structure.

The highest degree centrality is recorded for node 1 (Sumy), with a value of 0.18, confirming its role as the primary structural hub of the regional transport network. This reflects not only its administrative status as the oblast centre, but also its function as the main point of convergence for inter-settlement transport links. Together with nodes 35 (0.14), 21 (0.12), 13 (0.10), and Sumy (0.18) forms the structural core of the network. Nodes with degree centrality values of 0.10 and higher constitute a compact group of dominant hubs that concentrate a disproportionate share of direct connections and ensure the overall coherence of the network.

A larger group of nodes is characterised by moderate degree centrality values, typically ranging from 0.06 to 0.08. This group includes numerous territorial community centres (e.g. nodes 18, 23, 24, 37, 46, 49, and 51) that function as local and subregional connectors. Although they do not dominate the network at the regional scale, their relatively dense local connectivity supports intra-regional accessibility and reduces excessive dependence on the primary hub. In spatial terms, these nodes contribute to partial decentralisation of transport flows and increase the robustness of the network structure.

FOR AUTHOR USE ONLY

At the opposite end of the spectrum, nodes with very low degree centrality values (0.02-0.04) represent peripheral or linearly embedded elements of the transport system. These nodes typically occupy marginal positions within elongated or dendritic sections of the network and maintain only a limited number of direct connections. Their low degree centrality indicates increased vulnerability to network disruptions, as even minor changes in connectivity may substantially affect their accessibility. From a spatial planning perspective, such nodes are more likely to experience constraints in mobility and a stronger dependence on intermediary centres.

Overall, the observed pattern demonstrates that degree centrality effectively captures the local connectivity dimension of transport accessibility in Sumy Oblast. The coexistence of a clearly defined structural core, a broad intermediate layer of locally important connectors, and a peripheral group of weakly connected nodes confirms a pronounced core – periphery organisation of the network. While degree centrality does not account for global positional importance, it provides a robust

baseline for interpreting subsequent analyses based on closeness and betweenness centrality, which allow a more comprehensive assessment of regional accessibility and structural vulnerability.

4.2.2. Closeness Centrality ***Cc(v)*** is a key metric for assessing transport accessibility, as it reflects how quickly other nodes in the network can be reached from a given location. A node with a high closeness centrality value occupies a structurally central position within the network, meaning that it can access all other nodes with relatively short cumulative travel distances. In transport-geographical terms, such nodes function as highly efficient points of interaction, enabling rapid movement of people, goods, and services across the region.

High closeness centrality values are typically characteristic of major community centres that perform the role of logistical hubs, transport interchanges, or settlements with substantial passenger flows. In contrast, low closeness centrality is typical of peripheral communities, where access to most other centres requires long travel distances. These are often border communities or weakly connected settlements located at the margins of the transport network. Therefore, the assessment of transport accessibility based on closeness centrality is particularly important for understanding overall transport efficiency, identifying structurally important centres, and delineating peripheral zones within the regional transport system.

FOR AUTHOR USE ONLY

From a methodological perspective, closeness centrality values in the analysed network are normalised and range between approximately 0.15 and 0.31, which ensures comparability across nodes and allows direct interpretation of relative accessibility levels. The distribution of closeness centrality is moderately right-skewed, indicating the presence of a limited number of highly accessible nodes contrasted with a larger group of settlements characterised by lower transport efficiency.

Based on the observed value ranges, three broad groups of nodes can be distinguished. Nodes with $Cc \geq 0.26$ form the core of the transport network, characterised by minimal cumulative distances to all other centres and high systemic accessibility. Values in the range of approximately 0.21-0.25 correspond to intermediate or transit nodes, which provide relatively efficient access but do not

occupy fully central positions. Nodes with $Cc \leq 0.18$ represent the peripheral zone, where access to most other centres requires long travel distances, reflecting structural marginality within the network.

The results of the calculations (Table 5) indicate that the most accessible nodes in terms of transport efficiency are Sumy (0.3125), which clearly emerges as the most important node in the network, ensuring highly efficient connections with all other parts of the region. High closeness centrality values are also observed for Bilopillia (0.2959), Vorozhba (0.2841), Putyvl (0.2646), and Lebedyn (0.2660). These territorial community centres occupy the most advantageous positions in the network in terms of minimising travel distances across the entire system. Their location at the intersections of transport corridors linking different parts of Sumy Oblast explains their high accessibility and functional importance.

Table 5

Closeness centrality values of Sumy Oblast transport network nodes

Ordered by node ID		Ordered by descending centrality	
Node ID	**Closeness centrality**	**Node ID**	**Closeness centrality**
1	0.0193	35	0.4783
2	0.0048	13	0.3773
3	0.0077	24	0.3655
4	0.2190	7	0.2698
5	0.0682	49	0.2501
6	0.0021	48	0.2274
7	0.2698	8	0.2273
8	0.2273	4	0.2190
9	0.0015	12	0.2056
10	0.0028	51	0.1966
11	0.0026	21	0.1712
12	0.2056	18	0.1601
13	0.3773	17	0.1296
14	0.0007	32	0.1271
15	0.0895	39	0.1105
16	0.0515	15	0.0895
17	0.1296	5	0.0682
18	0.1601	40	0.0664
19	0.0006	16	0.0515
20	0.0012	44	0.0503
21	0.1712	34	0.0455
22	0.0059	42	0.0329
23	0.0038	27	0.0224
24	0.3655	1	0.0193
25	0.0067	36	0.0181

FOR AUTHOR USE ONLY

Ordered by node ID		Ordered by descending centrality	
Node ID	Closeness centrality	Node ID	Closeness centrality
26	0.0068	37	0.0180
27	0.0224	28	0.0139
28	0.0139	3	0.0077
29	0.0031	26	0.0068
30	0.0041	25	0.0067
31	0.0007	22	0.0059
32	0.1271	38	0.0058
33	0.0009	45	0.0055
34	0.0455	2	0.0048
35	0.4783	30	0.0041
36	0.0181	23	0.0038
37	0.0180	41	0.0036
38	0.0058	29	0.0031
39	0.1105	10	0.0028
40	0.0664	11	0.0026
41	0.0036	47	0.0025
42	0.0329	6	0.0021
43	0.0012	9	0.0015
44	0.0503	50	0.0015
45	0.0055	46	0.0014
46	0.0014	20	0.0012
47	0.0025	43	0.0012
48	0.2274	33	0.0009
49	0.2501	31	0.0007
50	0.0015	14	0.0007
51	0.1966	19	0.0006

Note: Node numbers correspond to the settlement names shown in Figure 1.

FOR AUTHOR USE ONLY

As expected, Sumy demonstrates the highest values of both closeness centrality (*Cc*) and degree centrality (*Dc*), which confirms its role as the key node ensuring the connectivity and efficiency of the entire transport network (Table 5). A similar conclusion can be drawn for Putyvl, which also plays a critical role in maintaining regional accessibility. Bilopillia and Vorozhba exhibit high closeness centrality despite relatively lower degree centrality values, indicating that their favourable accessibility is not primarily driven by a large number of direct connections, but rather by their strategic position within the network structure. Lebedyn demonstrates a comparable pattern. This combination of moderate connectivity and high accessibility highlights the structural importance of these centres and distinguishes them from nodes whose centrality is based mainly on the number of direct links.

Table 6

Top-5 nodes by Closeness Centrality and their comparison with Degree Centrality

Graph node ID	Community centre	Closeness centrality (*Cc*)	Degree centrality (*Dc*)
1	Sumy	0.3125	0.18
5	Bilopillia	0.2959	0.06
12	Vorozhba	0.2841	0.06
25	Lebedyn	0.2660	0.06
35	Putyvl	0.2646	0.14

At the opposite end of the spectrum, the lowest closeness centrality values are observed for Seredyna-Buda (0.1524), Hrun (0.1629), and Druzhba (0.1543), all of which are located on the periphery of the regional transport network. Svesa (0.1706) and Boromlia (0.1656) also exhibit low accessibility, reflecting their remote geographical position and limited integration into the main transport corridors. These results clearly indicate pronounced spatial inequalities in transport accessibility, with peripheral communities facing systematically longer travel distances to reach most other centres in the region.

FOR AUTHOR USE ONLY

Table 7

Peripheral Nodes by Closeness Centrality and Comparison with Degree Centrality

Graph node ID	Community centre	Closeness centrality (*Cc*)	Degree centrality (*Dc*)
40	Seredyna-Buda	0.1524	0.04
15	Khutir-Mykhailivskyi	0.1543	0.06
14	Hrun	0.1629	0.04
39	Svessa	0.1706	0.06
6	Boromlia	0.1661	0.06

Beyond the identification of nodes with high and low accessibility, it is crucial to identify centres that are critical for maintaining overall network cohesion. In particular, attention should be paid to nodes that form transport corridors. Such nodes may not necessarily have the highest closeness centrality values, yet they ensure key transitions between different parts of the network and therefore play a disproportionate role in sustaining connectivity.

In this context, Shostka (Cc = 0.2083) plays an important role in linking peripheral areas with the central part of the transport network. Although its closeness centrality is not among the highest, its removal would significantly affect network

connectivity. Shostka maintains direct links with important centres of neighbouring communities, such as Yampil and Znob-Novhorodske, making it a key node for preserving the integrity of the regional transport system. Similarly, Romny, with a relatively high closeness centrality value (0.2262), plays an important role in ensuring rapid access to multiple parts of the oblast. Both Shostka and Romny function as major transit nodes through which key transport routes pass, and their efficiency strongly influences overall travel times within the network.

Certain nodes, due to their strategic location, limited availability of alternative routes, and specific natural constraints, may act as potential bottlenecks, causing significant deterioration in transport accessibility if disrupted. To identify such bottlenecks, the baseline value of the average path length (APL) was first calculated for the entire network. Subsequently, each node was sequentially removed, and a new value of average path length (APL′) was computed. The comparison of these values allows the estimation of the increase in average route length (ΔAPL) and the relative increase in travel time across the network.

FOR AUTHOR USE ONLY

Among the most critical bottlenecks is node 1 (Sumy), which, despite being the most integrated node in the network, represents a point of heightened vulnerability. Any disruption in its functioning leads to a substantial increase in average travel distances across the entire system. The removal of this node results in an increase in average path length of approximately 15-20%, confirming its role as a potential bottleneck and underscoring the high level of dependence of the regional transport system on the oblast centre. Alternative routes exist, but they are considerably longer and less efficient, which significantly increases overall transport costs and travel time.

A similar bottleneck function is performed by Putyvl, which provides a crucial connection between the northern and southern parts of Sumy Oblast and facilitates crossing of the Seim River. Putyvl ranks among the top five nodes in terms of both degree and closeness centrality, highlighting its importance for transport accessibility. The Seim River constitutes a natural barrier, and the limited number of bridges significantly increases the vulnerability of this transport corridor. If Putyvl were to become inaccessible, a large share of routes would require detours via Konotop,

leading to increased travel distances and costs. Recalculation of shortest paths shows that disruption of transport connections through Putyvl would increase the average route length by approximately 12-18%.

Similar characteristics are observed for Konotop (Cc = 0.2475), which, like Putyvl, connects several major transport routes and functions as a key transit node between different parts of the oblast. Although Putyvl exhibits a higher closeness centrality value, indicating a greater number of efficient alternative routes, Konotop remains critically important due to its role in interregional transit. Additionally, Khutir-Mykhailivskyi (Cc = 0.1543) plays a crucial role in maintaining connectivity with the Svesa and Znob-Novhorodske communities. Disruption at this node would lead to partial isolation of these areas or force long detours, further reinforcing peripheralisation processes.

Overall, the analysis of closeness centrality reveals a spatially differentiated, clearly structured, polycentric model transport network characterised by a small number of highly accessible core nodes (a core of highly accessible communities), a belt of transit hubs, and a periphery with increased transport costs with limited accessibility. These findings complement the results obtained from degree centrality analysis and provide a more nuanced understanding of transport efficiency, vulnerability, and spatial inequality within the regional transport system.

FOR AUTHOR USE ONLY

4.2.3. Betweenness centrality $C_b(v)$ is a key indicator for identifying nodes that play a mediating role in the transport network by lying on the shortest paths between other pairs of nodes. Unlike degree or closeness centrality, which primarily reflect local connectivity or overall accessibility, betweenness centrality captures the extent to which a node controls or channels transport flows through the network. In transport-geographical terms, this metric is particularly important for the identification of transit hubs, structural bottlenecks, and nodes whose disruption may disproportionately affect the efficiency and stability of the entire transport system.

Betweenness centrality values obtained for the transport network of Sumy Oblast are normalised within the interval [0;1], which ensures full comparability between nodes regardless of network size and allows direct interpretation of relative transit

importance. Normalisation makes it possible to distinguish not only absolute leaders but also secondary transit nodes whose role might otherwise be underestimated in unscaled metrics.

The results of the calculations reveal a highly uneven distribution of betweenness centrality values (Table 8), indicating a pronounced right-skewed structure of the transport network. A limited number of nodes concentrate a dominant share of intermediary functions, while the majority of nodes perform marginal or predominantly terminal roles within the system. This configuration reflects the hierarchical organisation of the regional transport network and underscores the existence of structurally critical nodes whose functioning is essential for maintaining overall network connectivity.

Table 8

Betweenness centrality (*Bc*) values of Sumy Oblast transport network nodes

Ordered by node ID		Ordered by descending centrality	
Node ID	**Betweenness centrality (*Bc*)**	**Node ID**	**Betweenness centrality (*Bc*)**
1	0.5712	1	0.5712
2	0.0000	5	0.3474
3	0.1199	12	0.3175
4	0.0154	35	0.3017
5	0.3474	25	0.1886
6	0.0542	24	0.1876
7	0.0067	21	0.1764
8	0.0366	49	0.1246
9	0.0349	47	0.1227
10	0.1113	13	0.1223
11	0.0659	3	0.1199
12	0.3175	37	0.1141
13	0.1223	10	0.1113
14	0.0000	44	0.0894
15	0.0028	26	0.0695
16	0.0456	23	0.0676
17	0.0433	11	0.0659
18	0.0613	18	0.0613
19	0.0040	42	0.0577
20	0.0166	46	0.0555
21	0.1764	6	0.0542
22	0.0185	30	0.0516
23	0.0676	41	0.0494
24	0.1876	27	0.0476
25	0.1886	16	0.0456
26	0.0695	17	0.0433
27	0.0476	45	0.0400

FOR AUTHOR USE ONLY

Ordered by node ID		Ordered by descending centrality	
Node ID	**Betweenness centrality (*Bc*)**	**Node ID**	**Betweenness centrality (*Bc*)**
28	0.0000	8	0.0366
29	0.0000	9	0.0349
30	0.0516	43	0.0276
31	0.0000	33	0.0251
32	0.0000	22	0.0185
33	0.0251	39	0.0174
34	0.0000	20	0.0166
35	0.3017	4	0.0154
36	0.0000	51	0.0099
37	0.1141	7	0.0067
38	0.0000	19	0.0040
39	0.0174	15	0.0028
40	0.0000	2	0.0000
41	0.0494	14	0.0000
42	0.0577	28	0.0000
43	0.0276	29	0.0000
44	0.0894	31	0.0000
45	0.0400	32	0.0000
46	0.0555	34	0.0000
47	0.1227	36	0.0000
48	0.0000	38	0.0000
49	0.1246	40	0.0000
50	0.0000	48	0.0000
51	0.0099	50	0.0000

Note: Node numbers correspond to the settlement names shown in Figure 1.

FOR AUTHOR USE ONLY

The empirical distribution of betweenness centrality exhibits a strongly right-tailed pattern, which points to a marked structural asymmetry of the transport system. A small subset of nodes lies on a disproportionately large number of shortest paths, whereas most nodes display very low or zero betweenness values. Such a distribution is characteristic of spatial transport networks with a clearly expressed hierarchy and confirms the presence of a limited number of dominant transit corridors, rather than a uniformly meshed or evenly distributed network structure.

The highest value of C_b (0.5712) is observed for Sumy, indicating that the largest share of shortest paths within the network passes through this node. This clearly confirms the strategic role of the oblast centre as the principal hub ensuring transport accessibility to the remaining community centres of the region. Sumy functions not only as the most accessible node in terms of closeness centrality, but also as the dominant intermediary through which inter-community transport flows are channelled.

As a result, the transport system of Sumy Oblast exhibits a high degree of dependence on the uninterrupted functioning of this node (Table 9).

Table 9

Top 10 nodes by betweenness centrality

Graph node ID	Community centre	Betweenness centrality (*Bc*)
1	Sumy	0.5712
5	Bilopillia	0.3474
12	Vorozhba	0.3175
35	Putyvl	0.3017
25	Lebedyn	0.1886
24	Krolevets	0.1876
21	Konotop	0.1764
49	Shostka	0.1246
47	Chupakhivka	0.1227
13	Hlukhiv	0.1223

A second group of nodes with high betweenness centrality includes Bilopillia ($C_b \approx 0.347$), Putyvl ($C_b \approx 0.302$), and Vorozhba ($C_b \approx 0.317$). These centres play a decisive role in maintaining the connectivity of the transport system, despite their more moderate values of degree and closeness centrality. Their elevated C_b values indicate that they act as key transit gateways linking different parts of the oblast and ensuring continuity of transport corridors. Any restriction of access to any of these nodes would therefore lead to a significant redistribution of flows and an increase in average travel distances across the network.

FOR AUTHOR USE ONLY

Other centres listed in Table 9 also make an important contribution to maintaining network cohesion. In particular, Krolevets and Lebedyn ($C_b \approx 0.188$) serve as intermediary nodes linking peripheral areas with the central part of the network. Their role is especially important for reducing spatial isolation and preventing fragmentation of the transport system. Konotop ($C_b = 0.1764$) traditionally performs the function of a major transport corridor, facilitating movement between different parts of the region and ensuring interregional connectivity. Although its betweenness centrality is lower than that of Sumy or Putyvl, its strategic position within the network makes it a critical element of the regional transport structure.

Nodes with $Bc \geq 0.10$ form a distinct group that can be interpreted as the transit backbone (structural core) of the regional transport network. These nodes act as

obligatory intermediaries for a significant proportion of shortest routes between other community centres. Their functional role goes beyond local accessibility and directly affects network-wide efficiency, resilience, and vulnerability. Disruption of transport links at these nodes is likely to cause a non-linear increase in travel distances, rerouting of flows, and partial fragmentation of the network.

At the opposite end of the spectrum, a substantial number of nodes are characterised by very low or zero betweenness centrality values. These nodes play a marginal role in mediating transport flows and function predominantly as terminal or locally oriented centres within the network. They are weakly involved in inter-community transit and primarily serve short-distance or intra-local connectivity.

The absence of these nodes from the set of shortest paths indicates either the availability of alternative routes that bypass them or their peripheral structural position within the transport network. Although such centres may retain importance at the local scale, their contribution to overall network cohesion and long-distance transport efficiency is limited. From the perspective of system-wide stability, these nodes are therefore less critical; however, their peripheral position makes them more susceptible to isolation and declining accessibility, particularly under conditions of constrained transport investment or infrastructure degradation.

FOR AUTHOR USE ONLY

Overall, the analysis of betweenness centrality pattern reflects a hierarchical, corridor-oriented transport structure, in which a small number of strategically located centres control the majority of interregional flows. This configuration enhances efficiency under normal operating conditions but simultaneously increases systemic vulnerability to disruptions affecting key transit centres. This finding provides a robust structural basis for the subsequent identification of key transit nodes, bottlenecks, and zones of increased transport vulnerability. From the perspective of spatial planning and regional development, these findings highlight the need to strengthen alternative routes, diversify transport corridors, and reduce excessive dependence on individual nodes, particularly in the context of increasing geopolitical, economic, and infrastructural risks.

4.2.4. Eigenvector centrality ***(Ec)*** is a graph-theoretical metric that captures a qualitatively different dimension of transport accessibility compared to degree, closeness, or betweenness centrality. While the latter metrics primarily reflect the number of direct connections, overall accessibility, or the role of a node in mediating shortest paths, eigenvector centrality evaluates the structural embeddedness of a node within the network by taking into account not only its direct connections, but also the importance of the nodes to which it is connected.

In formal terms, eigenvector centrality assigns higher values to nodes that are connected to other nodes with high centrality scores. Consequently, a node may achieve a high *Ec* value even with a relatively modest number of direct connections, provided that these connections link it to structurally influential parts of the network. From a transport-geographical perspective, this metric allows the identification of centres whose importance derives not from administrative status, traffic volume, or transit dominance, but from their inclusion in a network core composed of mutually reinforcing, highly connected settlements.

FOR AUTHOR USE ONLY

Unlike degree or closeness centrality, eigenvector centrality does not directly measure accessibility or travel efficiency. Instead, it reflects a node's positional power within the overall network architecture. In human geography terms, *Ec* is particularly useful for identifying latent or indirect centres of influence, structural backbones of regional connectivity, and hierarchies of interaction that may remain invisible when relying solely on distance- or flow-based indicators.

The calculated eigenvector centrality values for the transport network of Sumy Oblast exhibit a strongly right-skewed (right-tailed) distribution, with a small number of nodes concentrating a disproportionately large share of the total structural influence, while the majority of nodes display very low *Ec* values. Such a distribution is typical for hierarchical transport systems characterised by uneven development, historical layering of infrastructure, and differentiated levels of regional integration.

All values are normalised and fall within the interval [0;1], which ensures their comparability across the network. However, in contrast to degree or closeness centrality, where values tend to be more evenly spread, eigenvector centrality

demonstrates a pronounced stratification, clearly separating a narrow structural core from a broad peripheral zone.

This pattern reflects the fact that only a limited number of centres are embedded in dense clusters of mutually influential nodes, while most settlements are connected primarily to nodes of low structural importance. As a result, eigenvector centrality reveals a deeper level of network hierarchy that goes beyond simple measures of accessibility or connectivity (Table 10).

Table 10

Eigenvector centrality (*Bc*) values of Sumy Oblast transport network nodes

Ordered by node ID		Ordered by descending centrality	
Node	**Eigenvector centrality**	**Node**	**Eigenvector centrality (Ec)**
1	0.0193	35	0.4783
2	0.0048	13	0.3773
3	0.0077	24	0.3655
4	0.2190	7	0.2698
5	0.0682	49	0.2501
6	0.0021	48	0.2274
7	0.2698	8	0.2273
8	0.2273	4	0.2190
9	0.0015	12	0.2056
10	0.0028	51	0.1966
11	0.0026	21	0.1712
12	0.2056	18	0.1601
13	0.3773	17	0.1296
14	0.0007	32	0.1271
15	0.0895	39	0.1105
16	0.0515	15	0.0895
17	0.1296	5	0.0682
18	0.1601	40	0.0664
19	0.0006	16	0.0515
20	0.0012	44	0.0503
21	0.1712	34	0.0455
22	0.0059	42	0.0329
23	0.0038	27	0.0224
24	0.3655	1	0.0193
25	0.0067	36	0.0181
26	0.0068	37	0.0180
27	0.0224	28	0.0139
28	0.0139	3	0.0077
29	0.0031	26	0.0068
30	0.0041	25	0.0067
31	0.0007	22	0.0059
32	0.1271	38	0.0058
33	0.0009	45	0.0055

FOR AUTHOR USE ONLY

Ordered by node ID		Ordered by descending centrality	
Node	**Eigenvector centrality**	**Node**	**Eigenvector centrality (Ec)**
34	0.0455	2	0.0048
35	0.4783	30	0.0041
36	0.0181	23	0.0038
37	0.0180	41	0.0036
38	0.0058	29	0.0031
39	0.1105	10	0.0028
40	0.0664	11	0.0026
41	0.0036	47	0.0025
42	0.0329	6	0.0021
43	0.0012	9	0.0015
44	0.0503	50	0.0015
45	0.0055	46	0.0014
46	0.0014	20	0.0012
47	0.0025	43	0.0012
48	0.2274	33	0.0009
49	0.2501	31	0.0007
50	0.0015	14	0.0007
51	0.1966	19	0.0006

Note: Node numbers correspond to the settlement names shown in Figure 1.

FOR AUTHOR USE ONLY

The highest eigenvector centrality value is observed for node 35 ($Ec = 0.4783$), which clearly dominates the network in terms of structural embeddedness. This node is closely followed by node 13 ($Ec = 0.3773$) and node 24 ($Ec = 0.3655$). Together, these centres form a compact spectral core of the transport network.

What distinguishes these nodes is not merely their connectivity, but their position within a tightly interconnected group of influential centres. Their high Ec values indicate that they are connected to other nodes that are themselves structurally important, creating a reinforcing pattern of mutual significance. In transport-geographical terms, these centres function as second-order cores – settlements whose importance emerges from network topology rather than from formal administrative or demographic dominance.

Importantly, these nodes do not necessarily coincide with the most accessible or most central nodes according to closeness or betweenness centrality. Instead, they represent a layer of influence rooted in historical development, spatial positioning along key corridors, and long-standing patterns of interaction. This finding underscores

the polycentric nature of the regional transport system and challenges simplified core – periphery interpretations based solely on administrative hierarchy.

A second group of nodes, characterised by eigenvector centrality values between approximately 0.20 and 0.30, includes nodes 7, 49, 48, 8, 4, 12, and 51. These centres form an extended core or stabilising belt surrounding the spectral nucleus of the network.

Although their *Ec* values are lower than those of the dominant core nodes, they nonetheless play an essential role in maintaining the integrity and cohesion of the transport system. These nodes serve as connectors between the spectral core and the wider network, reinforcing the influence of the core and enabling its effects to propagate spatially.

From a human geography perspective, this group corresponds to settlements that may not be perceived as primary centres but nonetheless contribute significantly to regional cohesion. Their position suggests a capacity to absorb or transmit structural influence, making them important candidates for targeted infrastructure development aimed at strengthening network resilience.

FOR AUTHOR USE ONLY

Nodes with eigenvector centrality values in the range of approximately 0.10-0.20 represent a semi-peripheral layer of the network. This group includes nodes 21, 18, 17, 32, and 39, which occupy an intermediate position between the structurally dominant core and the clearly peripheral areas.

These centres are neither marginal nor central in spectral terms. Instead, they represent zones of potential transition, whose future role within the network may change depending on infrastructural investments, shifts in transport flows, or broader socio-economic dynamics. In human geography, such nodes often correspond to settlements with latent development potential, capable of enhancing their network significance if integrated more strongly into high-capacity corridors or multi-directional linkages.

The majority of nodes in the network exhibit very low eigenvector centrality values ($Ec < 0.10$), forming a broad spectral periphery. This group includes many

settlements that may appear important according to other metrics, including administrative centres and nodes with relatively high degree or closeness centrality.

A particularly noteworthy example is node 1 (Sumy), which, despite its dominant position in terms of degree centrality, closeness centrality, and betweenness centrality, exhibits a very low eigenvector centrality value ($Ec = 0.0193$). This apparent paradox highlights the conceptual specificity of eigenvector centrality.

The lowEc value of Sumy indicates that, while it is highly connected and plays a critical role in ensuring accessibility and transit flows, it is primarily linked to nodes that themselves possess low structural influence. In other words, Sumy functions as a hierarchical and administrative hub rather than as a member of the network's spectral elite. Its importance is derived from its role as a terminal and distributor of flows, not from its integration into a mutually reinforcing cluster of influential centres.

This distinction is of fundamental importance for human geography. It demonstrates that administrative dominance and network influence do not necessarily coincide, and that different forms of centrality reflect different spatial logics of interaction, power, and dependency.

FOR AUTHOR USE ONLY

The analysis of eigenvector centrality reveals a layered and internally differentiated structure of the transport network of Sumy Oblast. The existence of a narrow spectral core, an extended stabilising belt, and a wide peripheral zone points to a polycentric but strongly hierarchical system, where influence is concentrated in a limited number of mutually connected centres.

Eigenvector centrality complements degree, closeness, and betweenness centrality by uncovering hidden dimensions of network organisation that are not captured by accessibility or transit-based measures. In particular, it highlights the presence of structurally influential centres whose role may be underestimated in conventional transport analyses.

From a planning and policy perspective, these findings suggest that interventions aimed solely at improving accessibility to the regional centre may reinforce existing hierarchies without enhancing overall network resilience. In contrast, strengthening connections among nodes within the spectral core and between the core and the semi-

periphery may yield greater systemic benefits by redistributing influence and reducing structural vulnerability.

Overall, eigenvector centrality provides critical insight into the deep structure of the regional transport network, revealing patterns of embeddedness, influence, and latent hierarchy that are essential for a comprehensive understanding of transport accessibility in a human-geographical context.

4.3. Comparative Synthesis of Centrality Metrics: A Two-Layer Structure of Transport Centrality

The joint interpretation of degree (*Dc*), closeness (*Cc*), betweenness (*Bc*), and eigenvector (*Ec*) centrality reveals that the transport network of Sumy Oblast is characterised by a two-layer structure of centrality, in which hierarchical dominance and structural embeddedness do not necessarily coincide. This multidimensional perspective allows moving beyond a unilinear understanding of "central" versus "peripheral" locations and instead exposes the differentiated roles played by community centres within the regional transport system.

FOR AUTHOR USE ONLY

At the first analytical layer, formed by *Dc*, *Cc*, and *Bc*, centrality is expressed primarily through functional accessibility and flow control. Degree centrality highlights nodes with a high number of direct connections, forming the structural skeleton of the network. Closeness centrality captures the efficiency of reaching other centres, reflecting the spatial logic of minimised travel distances. Betweenness centrality, in turn, identifies nodes that concentrate shortest paths and therefore exert control over transit flows. Taken together, these metrics outline a hierarchical and partially radial configuration, in which a limited number of centres act as dominant hubs ensuring overall connectivity and transport efficiency.

The combined interpretation of degree centrality (*Dc*), closeness centrality (*Cc*), and betweenness centrality (*Bc*) provides a multidimensional understanding of transport accessibility that cannot be achieved through any single metric alone. While each indicator captures a distinct structural property of the transport network, their joint

analysis reveals the functional roles of territorial community centres within the regional system of mobility, interaction, and service provision.

From a methodological perspective, degree centrality reflects local connectivity, indicating how many direct transport links a settlement maintains with neighbouring centres. Closeness centrality captures global accessibility, expressing how efficiently a given centre can reach all other nodes in the network via shortest paths. Betweenness centrality, in turn, identifies transit significance, highlighting nodes that act as intermediaries through which a large share of inter-nodal flows is channelled. Together, these metrics form a coherent analytical framework for distinguishing between structurally central, functionally strategic, and marginal elements of the transport network.

The comparison of *Dc*, *Cc*, and *Bc* values clearly demonstrates that structural centrality is not a uniform phenomenon. Certain centres, most notably Sumy, combine high values across all three indicators. Such nodes constitute the core of the regional transport system, simultaneously characterised by strong local connectivity, high global accessibility, and a dominant transit role. In human-geographical terms, these centres function as nodal points of spatial organisation, concentrating administrative functions, economic activities, and service provision. Their high betweenness values also indicate a pronounced systemic dependency: disruptions affecting these nodes are likely to propagate throughout the entire region, amplifying spatial vulnerability.

FOR AUTHOR USE ONLY

Table 11 summarises the group of nodes that form the structural core and transit backbone of the transport network of Sumy Oblast, as identified through the combined analysis of degree (*Dc*), closeness (*Cc*), and betweenness (*Bc*) centrality measures. The joint consideration of these three metrics allows for a multidimensional assessment of transport accessibility, distinguishing between local connectivity, global accessibility, and intermediary (transit) significance.

From a methodological perspective, it is important to emphasise that all centrality values are normalised within the [0;1] interval, ensuring comparability between nodes and enabling a consistent interpretation of their relative importance within the network. The distribution of centrality values exhibits a pronounced right-

skewed (right-tailed) pattern, where a limited number of nodes concentrate disproportionately high centrality values, while the majority of settlements demonstrate moderate or low connectivity and accessibility. Such a distribution is characteristic of real-world transport networks and reflects hierarchical spatial organisation rather than uniform connectivity.

Table 11

Structural Core and Transit Framework of the Transport Network (*Dc–Cc–Bc*)

(nodes ordered by descending betweenness centrality)

Node ID	Community centre	Degree centrality (*Dc*)	Closeness centrality (*Cc*)	Betweenness centrality (*Bc*)	Dominant network role
1	Sumy	0.18	0.3125	0.5712	Primary regional core, dominant bottleneck
5	Bilopillia	0.06	0.2959	0.3474	Structurally central connector
12	Vorozhba	0.06	0.2841	0.3175	Intermediary hub, corridor node
35	Putyvl	0.14	0.2646	0.3017	Strategic transit bottleneck (river crossing)
25	Lebedyn	0.06	0.2660	0.1886	Peripheral – central connector
24	Krolevets	0.08	0.2463	0.1876	Transition node between core and periphery
21	Konotop	0.12	0.2475	0.1764	Interregional transit hub
49	Shostka	0.08	0.2146	0.1246	Secondary connector
47	Chupakhivka	0.06	0.1953	0.1227	Local transit node
13	Hlukhiv	0.10	0.2101	0.1223	Supporting structural node
3	Bezdryk	0.06	0.2525	0.1199	Locally connected intermediary
37	Romny	0.08	0.2294	0.1141	Corridor-supporting node
10	Verkhnia Syrovatka	0.06	0.1992	0.1113	Secondary transit role

FOR AUTHOR USE ONLY

Nodes included in Table 11 are characterised by elevated betweenness centrality ($Bc \geq 0.10$), which identifies them as critical intermediaries through which a substantial share of shortest paths in the network passes. This threshold effectively delineates a

group of structurally indispensable nodes whose functioning is essential for maintaining overall network cohesion. The oblast centre, Sumy, stands out as an extreme case, combining the highest values of *Bc*, *Cc*, and *Dc*. This confirms its dominant role not only as an administrative centre but also as the primary transport mediator whose disruption would have system-wide consequences.

At the same time, several secondary centres (e.g. Putyvl, Bilopillia, Vorozhba, Lebedyn, Konotop) demonstrate high betweenness combined with moderate degree centrality, indicating that their importance does not stem from a large number of direct connections, but rather from their strategic positionality within the network topology. These nodes function as gateways between different subregions, bridging core and peripheral areas and ensuring the continuity of transport corridors. In network-theoretical terms, they reduce global path lengths and enhance redundancy by providing alternative routes between otherwise weakly connected parts of the system.

The comparison between *Dc* and *Cc* within this group further highlights functional differentiation among core nodes. While some centres exhibit high values across all metrics, others compensate for lower local connectivity with high global accessibility, underscoring the importance of positional advantages over sheer link quantity. This confirms that transport centrality in the region is not solely determined by the density of connections, but rather by the spatial configuration of nodes within the broader network structure.

FOR AUTHOR USE ONLY

Overall, Table 11 captures the functional skeleton of the regional transport network, identifying nodes that concentrate flows, mediate interactions, and sustain system-wide accessibility. These centres represent priority locations for infrastructure protection, capacity enhancement, and resilience-oriented planning, as their disruption would lead to disproportionate increases in travel distances and network fragmentation.

A second group of centres is defined by high closeness centrality combined with moderate or relatively low degree centrality. Examples include Bilopillia, Vorozhba, Lebedyn, and, to a slightly lesser extent, Putyvl. These settlements do not necessarily possess a large number of direct connections, yet they are strategically positioned within the network in such a way that shortest paths to most other centres remain

relatively short. This configuration reflects a form of structural embeddedness rather than local dominance. From the standpoint of human geography, such centres often serve as efficient intermediaries between core and peripheral areas, enabling spatial cohesion despite limited infrastructural density.

A distinct role is played by centres with elevated betweenness centrality but only moderate closeness and degree values, such as Putyvl, Konotop, and Krolevets. These nodes act as transit gateways or corridor hubs, frequently located at the intersection of radial and transversal routes or near natural barriers such as rivers. Their importance lies not in overall accessibility but in their capacity to mediate flows between otherwise weakly connected parts of the region. In spatial-planning terms, these centres represent critical control points within the transport system, where infrastructural failures or capacity constraints may lead to disproportionate increases in travel time and regional fragmentation.

In contrast, the peripheral part of the network is characterised by centres exhibiting low values across all three centrality measures. These nodes typically show minimal degree centrality, low closeness centrality, and negligible betweenness centrality, indicating both weak local integration and marginal participation in interregional flows. Such settlements are often located along terminal branches of the network or near administrative and state borders. From a human-geographical perspective, they occupy a position of structural peripherality, where limited transport accessibility reinforces socio-economic disadvantages, restricts access to higher-order services, and contributes to cumulative processes of marginalisation.

FOR AUTHOR USE ONLY

Table 12 presents a contrasting group of nodes characterised by low values across all three centrality measures, delineating the peripheral and structurally weak segment of the transport network. These nodes are typified by minimal betweenness centrality ($Bc \approx 0$), indicating that they do not participate in the formation of shortest paths between other settlements and therefore play no meaningful role in mediating transport flows at the regional scale.

Methodologically, the near-zero Bc values observed for this group are particularly significant. In graph-theoretical terms, such nodes are not involved in

global network cohesion; their removal would have little to no effect on overall path lengths or connectivity between other centres. This property clearly distinguishes them from transit nodes and confirms their classification as terminal or branch elements of the network rather than integrative components.

Table 12

Peripheral and Structurally Weak Nodes of the Transport Network (*Dc–Cc–Bc*)

(nodes characterised by low degree, low closeness, and negligible betweenness centrality)

Node ID	Community centre	Degree centrality (*Dc*)	Closeness centrality (*Cc*)	Betweenness centrality (*Bc*)	Structural interpretation
28	Mykolaivka (village)	0.02	0.1773	0.0000	Terminal peripheral node
38	Sad	0.02	0.1866	0.0000	Weakly integrated local centre
31	Nyzhnia Syrovatka	0.02	0.1887	0.0000	Linear peripheral node
48	Shalyhine	0.04	0.2075	0.0000	Local node without transit role
14	Hrun	0.04	0.1629	0.0000	Deep peripheral node
40	Seredyna-Buda	0.04	0.1524	0.0000	Extreme peripheral node
29	Myropillia	0.04	0.1992	0.0000	Locally connected, no transit function
32	Nova Sloboda	0.02	0.1953	0.0000	Structurally isolated
2	Andriyashivka	0.02	0.1852	0.0000	Marginal node
50	Yunakivka	0.02	0.1706	0.0000	Peripheral branch node
36	Richky	0.02	0.1866	0.0000	Terminal settlement
34	Popivka	0.02	0.1931	0.0000	Weakly connected local centre
15	Druzhba	0.06	0.1543	0.0028	Peripheral node with minimal transit role
19	Kyrykivka	0.04	0.2101	0.0040	Marginal connector
7	Bochechky	0.04	0.1976	0.0067	Minor local intermediary
51	Yampil	0.08	0.2146	0.0099	Peripheral supporting node

FOR AUTHOR USE ONLY

Low degree centrality values (typically $Dc \leq 0.04\text{-}0.06$) further indicate a limited number of direct connections, often confined to a single main route or linear chain of settlements. Combined with low closeness centrality (generally $Cc \leq 0.18\text{-}0.20$), this pattern reflects both poor local connectivity and substantial cumulative distances to most other nodes in the network. In practical transport-geographical terms, residents of these settlements face systematically longer travel times and higher transport costs when accessing regional centres, services, or markets.

Spatially, the nodes listed in Table 12 tend to occupy marginal positions within the oblast, frequently located near administrative borders or within sparsely connected northern and north-eastern sectors. Their peripheralisation is therefore not accidental but structurally embedded in the topology of the transport network, reinforcing core – periphery gradients identified in earlier topological and closeness-based analyses.

Importantly, the interpretation of Table 12 highlights that peripheral nodes are not merely "less important" versions of central ones, but constitute a qualitatively different structural category. Their transport accessibility cannot be substantially improved through internal network optimisation alone, as they lack the positional leverage required to benefit from rerouting or redistribution of flows. Instead, any meaningful enhancement of accessibility for these areas would require exogenous interventions, such as the construction of new links, upgrading of road hierarchy, or the creation of alternative corridors connecting them more directly to the network core.

FOR AUTHOR USE ONLY

In summary, Table 12 delineates the zone of structural vulnerability and transport inertia within the regional system. These nodes are highly dependent on a small number of higher-order centres and routes, making them especially sensitive to disruptions and reinforcing long-term peripheralisation processes. Together with Table 11, this analysis confirms that the transport network of Sumy Oblast is characterised by a strongly hierarchical, right-skewed structure with a limited core of dominant nodes and an extensive peripheral belt with constrained accessibility.

The joint *Dc–Cc–Bc* analysis also highlights an important conceptual distinction between connectivity and accessibility. High local connectivity does not automatically translate into high global accessibility, nor does strong transit significance guarantee

favourable everyday mobility conditions for residents. This discrepancy is particularly relevant in the context of post-2020 administrative-territorial reform, where the designation of community centres did not always correspond to their actual position within the transport network. As a result, certain administrative centres may face functional constraints that undermine their capacity to serve surrounding territories effectively.

From a broader human geography perspective, the observed centrality patterns reflect the historical evolution of settlement systems, infrastructural investments, and natural constraints. The dominance of a limited number of core and transit nodes, combined with elongated peripheral branches, indicates a core – periphery structure with limited redundancy, especially in northern and north-eastern parts of Sumy Oblast. This configuration increases the sensitivity of the regional transport system to disruptions and accentuates spatial inequalities in accessibility.

In summary, the comparative interpretation of degree, closeness, and betweenness centralities confirms that transport accessibility in Sumy Oblast is a relational and hierarchical phenomenon, shaped by the interplay between network topology, spatial configuration, and functional roles of settlements. The integration of graph-theoretical metrics with a human geography framework allows not only the identification of structurally important nodes but also a deeper understanding of how transport networks condition regional cohesion, accessibility to services, and the everyday spatial practices of the population. This integrated perspective provides a robust analytical basis for transport planning, territorial development strategies, and policies aimed at reducing spatial disparities.

FOR AUTHOR USE ONLY

The eigenvector-based structure reveals a compact group of nodes – most notably Putyvl, Hlukhiv-related nodes, Krolevets-related connections, and several corridor-forming centres – that form a spectral core of the network. These centres may not dominate in terms of administrative importance or overall traffic volume, yet they are deeply embedded in a dense web of influential connections. Their importance lies in the mutual reinforcement of connectivity rather than in hierarchical dominance. From the standpoint of human geography, this layer reflects long-term infrastructural

co-evolution, corridor-based development, and historically stabilised interaction patterns.

It is precisely at this point that the so-called "Sumy paradox" becomes evident. Despite its overwhelming dominance in degree, closeness, and betweenness centrality, Sumy exhibits an exceptionally low eigenvector centrality. This discrepancy indicates that Sumy functions as a powerful hierarchical and transit hub, yet remains structurally weakly embedded within the network's spectral core. In other words, Sumy controls flows and accessibility, but it is not strongly connected to other structurally influential nodes that mutually reinforce each other's centrality.

This paradox does not represent a methodological inconsistency; rather, it exposes a fundamental spatial distinction between command centrality and embedded centrality. Sumy's position corresponds to that of an exogenous control centre, whose dominance is maintained through administrative concentration, infrastructural convergence, and flow accumulation, rather than through dense reciprocal linkages with other high-centrality nodes. Conversely, the eigenvector core reflects a more polycentric and internally cohesive subsystem, shaped by corridor logic, historical transport alignments, and interdependent regional interactions.

FOR AUTHOR USE ONLY

From a broader human-geographical perspective, the two-layer structure of centrality highlights that regional transport systems cannot be adequately interpreted through a single metric or a single notion of "importance." Hierarchical dominance ensures system-wide accessibility and control, while spectral embeddedness ensures resilience, redundancy, and structural cohesion. The divergence between these layers suggests that vulnerability and robustness are unevenly distributed: disruptions at hierarchically dominant hubs may have immediate large-scale effects, whereas disruptions within the embedded core may undermine long-term structural stability.

In this sense, the combined *Dc–Cc–Bc–Ec* synthesis provides not only a descriptive account of network organisation, but also a conceptual framework for understanding spatial inequality, infrastructural dependency, and regional resilience. The transport network of Sumy Oblast thus appears not as a single-centre system, but

as a hybrid configuration, where hierarchical command and embedded interaction coexist, overlap, and occasionally contradict each other.

4.4. Integrated Interpretation of Transport Accessibility Patterns: Core–Transit–Periphery Model

The combined application of degree, closeness, and betweenness centrality measures enables a comprehensive interpretation of transport accessibility patterns in Sumy Oblast and reveals a clearly structured, hierarchical, and polycentric transport system. Unlike single-metric approaches, the integrated *Dc–Cc–Bc* framework allows differentiation between local connectivity, global accessibility, and intermediary (transit) significance, thereby providing a robust basis for spatial interpretation and planning-oriented conclusions.

4.4.1. Structural hierarchy of the transport network. The results consistently demonstrate a right-skewed distribution of centrality values, typical of real-world transport networks, where a limited number of nodes concentrate disproportionately high levels of connectivity and control over flows, while the majority of settlements remain weakly integrated. This confirms that the transport network of Sumy Oblast does not function as a homogeneous system, but rather as a hierarchically organised structure with pronounced core – periphery gradients.

FOR AUTHOR USE ONLY

At the top of this hierarchy stands a compact structural core, dominated by the oblast centre of Sumy. Its exceptionally high values across all three centrality measures (*Dc*, *Cc*, *Bc*) identify it as the principal integrative node, simultaneously fulfilling the roles of:

- a local hub with numerous direct connections (high *Dc*),
- a globally accessible centre minimising cumulative travel distances (high *Cc*),
- a dominant intermediary through which the majority of shortest paths pass (very high *Bc*).

This combination makes Sumy not merely a large node, but a system-forming element whose functioning is critical for the stability and efficiency of the entire regional transport system.

4.4.2. Transit belt and secondary integrative centres. Surrounding the core is a belt of transit and secondary integrative centres, including Putyvl, Konotop, Bilopillia, Vorozhba, Lebedyn, Romny, and Krolevets. These nodes are characterised by:

- moderate to high closeness centrality,
- elevated betweenness centrality (often exceeding the methodological threshold of $Bc \geq 0.10$),
- generally lower degree centrality compared to the core.

From a methodological standpoint, this configuration is particularly important. It demonstrates that transport importance is not synonymous with the number of direct connections. Instead, these centres derive their significance from their strategic positionality within the network topology, acting as bridges between different subregions and reducing overall path lengths.

In transport-geographical terms, this group forms the functional backbone of regional mobility, concentrating transit flows and ensuring continuity between the core and peripheral areas. Disruption of these nodes would not necessarily fragment the network entirely, but would substantially increase travel distances, reduce redundancy, and intensify accessibility inequalities.

FOR AUTHOR USE ONLY

4.4.3. Peripheral zone and structurally weak nodes. At the opposite end of the spectrum lies an extensive peripheral zone, composed of settlements with consistently low *Dc*, *Cc*, and *Bc* values. These nodes:

- have few direct connections,
- located far from most other centres in cumulative distance terms,
- play no meaningful role in mediating transport flows.

Their near-zero betweenness centrality confirms that they are terminal or linearly included nodes, whose presence does not contribute to overall network cohesion. From a spatial perspective, these settlements are typically located near administrative borders or in sparsely connected sectors of the oblast, reinforcing long-standing patterns of peripheralisation.

Crucially, the integrated analysis shows that peripheral status is structural rather than accidental. Improving accessibility in these areas cannot be achieved solely through optimisation of existing flows; instead, it requires targeted infrastructural interventions, such as new links or upgrades that alter their positional relationship to the network core.

4.4.4. Human geography implications. From a human geography perspective, the identified core – transit – periphery model has direct implications for population mobility, access to services, and regional development opportunities. Centres with high closeness and betweenness centrality offer residents faster and more reliable access to healthcare, education, labour markets, and administrative services, reinforcing their socio-economic attractiveness.

Conversely, peripheral communities face cumulative disadvantages associated with longer travel times, higher transport costs, and reduced interaction intensity. These transport-related constraints contribute to broader processes of demographic decline, economic marginalisation, and uneven territorial development, particularly in border and rural areas.

FOR AUTHOR USE ONLY

4.4.5. Synthesis and planning relevance. Overall, the integrated *Dc–Cc–Bc* analysis confirms that the transport network of Sumy Oblast operates as a polycentric yet strongly hierarchical system, with:

- a dominant core,
- a set of strategically positioned transit hubs,
- an extensive peripheral belt with limited accessibility.

This structure explains observed disparities in transport efficiency and provides a clear analytical foundation for evidence-based transport and regional planning. The identification of core and transit nodes highlights priority locations for infrastructure protection and resilience enhancement, while the delineation of peripheral zones underscores the need for targeted policies aimed at mitigating spatial inequality.

In this sense, graph centrality analysis proves to be not only a methodological tool, but also a conceptual bridge between transport geography and human geography, linking network structure with lived accessibility and regional development dynamics.

4.5. Typology of Community Centres Based on *Dc–Cc–Bc–Ec* Metrics

The combined interpretation of degree (*Dc)*, closeness (*Cc*), betweenness (*Bc*), and eigenvector (*Ec*) centrality enables the identification of a functionally and structurally differentiated typology of community centres within the transport network of Sumy Oblast. Rather than treating centrality as a unidimensional attribute, this approach reveals distinct roles of nodes, reflecting different modes of spatial influence, connectivity, and vulnerability. Four principal types of centres can be distinguished: hierarchical hubs, network brokers, embedded core nodes, and peripheral nodes (Table 13).

Table 13

Typology of Community Centres Based on *Dc–Cc–Bc–Ec* Metrics

Node type	Dominant metrics	Functional role in the transport network	Planning implications
Hierarchical hubs	High *Dc*, high *Cc*, very high *Bc*; low or moderate*Ec*	Act as primary command and concentration nodes; ensure maximum overall accessibility and control a large share of shortest paths; structurally dominant but weakly embedded in the spectral core	High vulnerability points: disruptions cause system-wide effects; priority for capacity reinforcement, redundancy creation, and risk mitigation; decentralisation of flows desirable to reduce over-dependence
Network brokers (transit / gateway nodes)	High *Bc*; moderate to high *Cc*; moderate *Dc*; variable *Ec*	Mediate flows between different subregions; function as bottlenecks and gateways along major corridors; critical for interregional and inter-subregional connectivity	Protection and maintenance of corridor continuity essential; targeted investments in bypasses, bridges, and alternative routes to reduce bottleneck risk
Embedded core nodes (spectral core)	High*Ec*; moderate *Dc* and *Cc*; moderate or low *Bc*	Form a dense, mutually reinforcing backbone of the network; support polycentric cohesion, redundancy, and long-term structural stability	Strengthening these nodes enhances network resilience; suitable anchors for polycentric development strategies and secondary growth poles
Peripheral nodes	Low *Dc*, low *Cc*, low *Bc*, negligible *Ec*	Weakly connected and poorly accessible; rarely involved in transit flows; structurally dependent on higher-order centres	Require targeted accessibility policies (feeder roads, public transport subsidies); without intervention, risk cumulative peripheralisation and socio-economic decline

FOR AUTHOR USE ONLY

1. Hierarchical Hubs. Hierarchical hubs are characterised by simultaneously high values of *Dc*, *Cc*, and *Bc*, indicating a strong concentration of direct connections, superior overall accessibility, and a dominant role in controlling transit flows. These centres function as command nodes within the regional transport system, structuring mobility patterns and concentrating the majority of shortest paths.

Sumy represents the clearest example of this type. Its exceptionally high betweenness centrality confirms that a large proportion of regional routes are channelled through the oblast centre, while its high closeness centrality reflects minimal average travel distances to other nodes. Thus, according to all centrality metrics, Sumy demonstrates the highest level of transport accessibility and the strongest influence on overall network connectivity. It exhibits the highest values of degree centrality (*Dc* = 0.18, the largest number of direct connections), closeness centrality (*Cc* = 0.3125, the shortest average distance to all other nodes), and betweenness centrality (*Bc* = 0.5712, the most prominent transit node in the network).

At the same time, its eigenvector centrality remains relatively low (*Ec* = 0.0649), indicating that although Sumy itself is highly central, it is primarily connected to nodes. This configuration reflects a hierarchical but weakly embedded form of centrality, typical of administrative capitals whose dominance is imposed through institutional concentration rather than reciprocal network embeddedness.

FOR AUTHOR USE ONLY

In human-geographical terms, hierarchical hubs embody top-down spatial organisation, reinforcing monocentric tendencies and creating systemic dependence on a limited number of key nodes. While they enhance overall accessibility, they also represent points of heightened vulnerability, as disruptions at these nodes disproportionately affect network performance.

2. Network Brokers (Transit and Gateway Nodes). Network brokers are distinguished primarily by elevated betweenness centrality, often combined with moderate or high values of closeness centrality, but not necessarily by a high number of direct connections. Their importance lies in their role as bridges between different parts of the network, facilitating interregional or inter-subregional connectivity.

Putyvl, Konotop, Bilopillia, Vorozhba, Lebedyn, and Romny exemplify this category. These centres frequently lie along major transport corridors or at critical river crossings and junctions, where alternative routes are limited. Their removal or degradation would result in significant increases in average path length, indicating their function as structural bottlenecks.

Putyvl displays a slightly lower degree centrality ($Dc = 0.14$), while its closeness centrality ($Cc = 0.2646$) indicates one of the fastest average access times to other network nodes. Its betweenness centrality ($Bc = 0.3017$) confirms its frequent role as a critical transit point, and its eigenvector centrality ($Ec = 0.4579$) is the highest in the network. This combination of indicators identifies Putyvl as the second most important transport hub, through which a substantial share of regional transport flows passes. Consequently, any disruption of this node would have a pronounced negative impact on transport accessibility for a large number of territorial communities within Sumy Oblast.

FOR AUTHOR USE ONLY

Konotop is characterised by a degree centrality of $Dc = 0.12$, which is above the network average, and a relatively high closeness centrality ($Cc = 0.2475$), indicating good transport accessibility. Its betweenness centrality ($Bc = 0.1764$) suggests an important, though not critical, intermediary role, while its eigenvector centrality ($Ec = 0.2771$) places it among the most influential nodes in the network. Taken together, these indicators confirm that Konotop is well integrated into the regional transport system and plays a significant role in maintaining regional-level accessibility.

From a spatial perspective, network brokers represent functional gateways rather than hierarchical command centres. They mediate flows between core and periphery, north and south, or intra- and interregional systems. Their strategic importance often exceeds their demographic or administrative weight, underscoring the need to distinguish transit function from formal centrality.

3. Embedded Core Nodes (Spectral Core). Embedded core nodes are defined by high eigenvector centrality, indicating strong connectivity to other influential nodes, even if their *Dc*, *Cc*, or *Bc* values are moderate. These centres form a dense and

mutually reinforcing subsystem within the network, constituting its structural backbone in spectral terms.

Nodes such as Putyvl, Krolevets-related nodes, Hlukhiv-related nodes, and several corridor-based centres dominate this group. Their importance derives not from hierarchical dominance or flow concentration, but from reciprocal interdependence and long-term infrastructural co-evolution. These centres often align with historically established transport corridors and stable settlement systems.

In human geography, embedded core nodes correspond to polycentric cohesion, supporting network resilience, redundancy, and adaptive capacity. Unlike hierarchical hubs, they reduce systemic vulnerability by providing alternative pathways and distributed connectivity.

4. Peripheral Nodes. At the opposite end of the spectrum, three centres can be identified as having the lowest levels of transport accessibility. Peripheral nodes exhibit consistently low values across all centrality measures, particularly in *Dc*, *Cc*, and *Bc*, and often negligible eigenvector centrality. These centres are weakly connected, poorly accessible, and rarely involved in transit flows.

FOR AUTHOR USE ONLY

Examples include Seredyna-Buda, Hrun, Druzhba, Svesa, Kyrykivka, and other border or remote settlements. Their position reflects geographical remoteness, limited transport infrastructure, and historical marginalisation within the regional system. Peripheral nodes are structurally dependent on higher-order centres for access to services, markets, and mobility opportunities.

Hrun is characterised by a very limited number of connections ($Dc = 0.04$), extremely low closeness centrality ($Cc = 0.1629$), zero betweenness centrality ($Bc = 0.0$), and negligible eigenvector centrality ($Ec = 0.0023$). These values indicate that the settlement neither performs a transit function nor exerts any meaningful influence on overall network connectivity.

Kyrykivka exhibits a similarly low level of integration into the transport system of Sumy Oblast, with $Dc = 0.04$, $Cc = 0.1661$, $Bc = 0.0039$, and $Ec = 0.0023$. Its marginal role in transit flows and minimal structural influence reinforce its classification as a peripheral and weakly connected node.

One of the least integrated settlements within the regional transport network is Yunakivka, which demonstrates minimal degree centrality ($Dc = 0.02$), low closeness centrality ($Cc = 0.1953$), zero betweenness centrality ($Bc = 0.0$), and very low eigenvector centrality ($Ec = 0.0049$). These indicators consistently point to its peripheral position and limited role in ensuring regional transport connectivity.

From a human-geographical standpoint, peripheralisation is both a spatial and socio-economic process, reinforced by transport disadvantage. Limited accessibility contributes to cumulative decline, demographic loss, and reduced development potential, unless counterbalanced by targeted infrastructure or policy interventions.

Concluding Remarks on the Typology. This fourfold typology demonstrates that centrality in regional transport networks is inherently multidimensional. Hierarchical hubs ensure command and accessibility; network brokers sustain flow continuity; embedded core nodes provide structural resilience; peripheral nodes reveal spatial inequality and vulnerability. The coexistence of these types confirms that the transport network of Sumy Oblast operates neither as a purely monocentric nor as a fully polycentric system, but rather as a hybrid configuration shaped by both hierarchical control and embedded connectivity.

FOR AUTHOR USE ONLY

* * *

The joint interpretation of degree, closeness, betweenness, and eigenvector centrality demonstrates that the role of a community centre within the regional transport network cannot be reduced to a single indicator of importance. Each metric captures a different dimension of centrality: local connectivity (*Dc*), overall accessibility (*Cc*), control over transit flows (*Bc*), and structural embeddedness within the network core (*Ec*). When considered in isolation, these measures provide only partial insights; however, their combined analysis reveals a multi-layered and functionally differentiated structure of the transport system.

From a human geography perspective, this multidimensional centrality reflects not only infrastructural characteristics but also historically formed settlement

hierarchies, spatial constraints, and path-dependent development trajectories. The network thus exhibits a dual logic of organisation: on the one hand, a limited number of hierarchically dominant centres concentrating flows and accessibility; on the other, a set of structurally embedded nodes that ensure cohesion, redundancy, and long-term stability of the system. In parallel, several nodes perform intermediary brokerage functions, while others remain structurally peripheral.

To synthesise these patterns and translate quantitative metrics into interpretable spatial roles relevant for territorial planning, a typology of community centres was developed based on the dominant combinations of *Dc*, *Cc*, *Bc*, and *Ec*. The resulting classification links network position with functional role and planning relevance.

FOR AUTHOR USE ONLY

CHAPTER 5. LINKING CENTRALITY MEASURES WITH ISOCHRONE-BASED ACCESSIBILITY

Transport accessibility across Sumy Oblast demonstrates pronounced spatial disparities in travel time between community centres and the regional hub. This issue was assessed using graph-based modelling applied to the real-world road network, which connects local and district centres. The analysis employed graph connectivity metrics, topological distances, node centrality indices, and isochrone mapping techniques. A transportation graph comprising 51 nodes and 74 edges was constructed based on actual inter-settlement road connections. Topological accessibility was evaluated using shortest-path matrices, while connectivity indicators – such as average path length, clustering coefficient, network density, efficiency, and diameter – helped reveal the structural properties of the network.

FOR AUTHOR USE ONLY

Centrality measures – including degree, closeness, betweenness, and eigenvector centrality – were used to identify key transport hubs and peripheral settlements. Isochrone maps based on travel time visualized zones of one-, two-, and three-hour accessibility, highlighting infrastructure asymmetries and uneven connectivity across the oblast. The findings reveal that the central and western parts of Sumy Oblast are well connected to the regional centre, whereas northern and eastern peripheral areas exhibit structural isolation. Degree and eccentricity centrality further reflect the uneven integration of localities into the regional transport network. The results provide a valuable analytical basis for targeted infrastructure investments and spatial planning policies, particularly in the context of post-war recovery in Ukraine's affected regions.

Presented in this chapter analysis demonstrates that transport accessibility within districts is spatially heterogeneous. Isochrone-based modelling conducted for each district revealed substantial differences in travel times to key settlements, which are shaped by a combination of physical-geographical conditions and the structural characteristics of the road network.

5.1. Isochrone-based modelling of automobile transport accessibility

Konotop District. Konotop District exhibits a noticeably lower level of accessibility for many territorial communities to the district centre, which is located more eccentrically than in Sumy District (Fig. 2). The nearest settlements: Bochechky, Duboviazivka, and Popivka – can be reached within 30 minutes, whereas Putyvl and Nova Sloboda are positioned on the periphery of the transport network and require more than one hour to access the district centre.

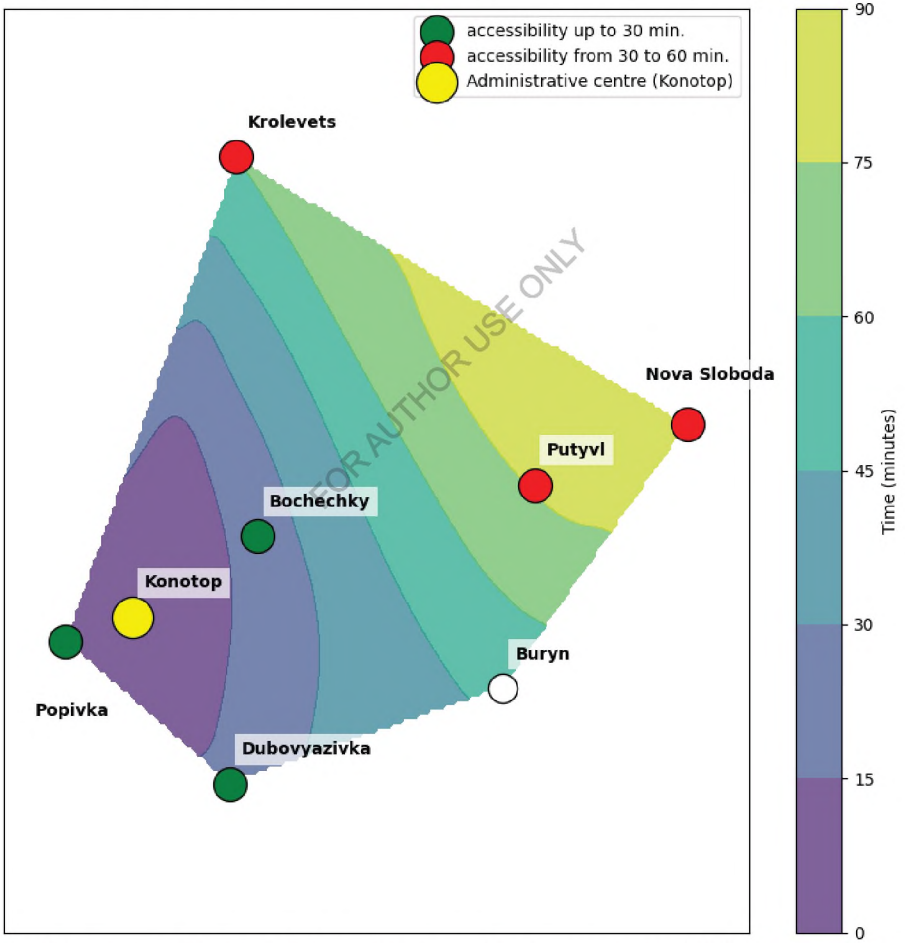


Fig. 2. Isochrones (15-minute intervals) of automobile transport accessibility from territorial community centres to district centre – Konotop (created in Matplotlib, visualised in Google Colab)

The remoteness of Nova Sloboda from the main transport corridors of Konotop District significantly reduces its accessibility, potentially constraining economic activity and affecting the socio-economic conditions of the community. At the same time, besides Konotop itself, several important transport centres have emerged within the district, facilitating inter-district connectivity. For example, Krolevets functions as a key transit node, ensuring transport accessibility for settlements of Shostka District.

A distinctive feature of Konotop District is the influence of natural barriers. The considerable spatial extent of the district and the limited number of bridges across the Seim River – which effectively divides Sumy Oblast into northern and southern parts – contribute to pronounced inequalities in accessibility. Certain settlements, notably Putyvl, may act as potential "bottlenecks", where disruptions could significantly impede mobility across the wider regional transport system.

Okhtyrka District. Okhtyrka District displays pronounced contrasts in transport accessibility. The settlements closest to Okhtyrka – Chernechchyna and Trostianets – exhibit the highest levels of accessibility, as they lie within the 30-minute isochrone. In contrast, Velyka Pysarivka, Chupakhivka, and Komyshi fall within zones exceeding 60 minutes of travel time (Fig. 3).

FOR AUTHOR USE ONLY

These disparities are primarily driven by the large spatial extent of the district and the peripheral location of its administrative centre. Kyrykivka represents a notable case: although it is located in relatively close geographical proximity to Okhtyrka, its travel time remains within the 45-60-minute range. This pattern reflects not distance per se, but rather the condition and capacity of the road network, highlighting the role of infrastructural constraints in shaping effective transport accessibility.

Romny District. Romny District is characterised by a relatively balanced pattern of transport accessibility between territorial community centres and the district centre (Fig. 4). Most settlements are located within a 30-60-minute travel-time zone, while Korovyntsi, Andriiashivka, and Khmeliv fall within the 30-minute isochrone, indicating strong connectivity with the district centre. The location of Romny at the intersection of major transport routes contributes to a more even spatial distribution of accessibility across the district. Only Synivka demonstrates weaker connectivity,

which can be attributed to its peripheral position and less developed road infrastructure here.

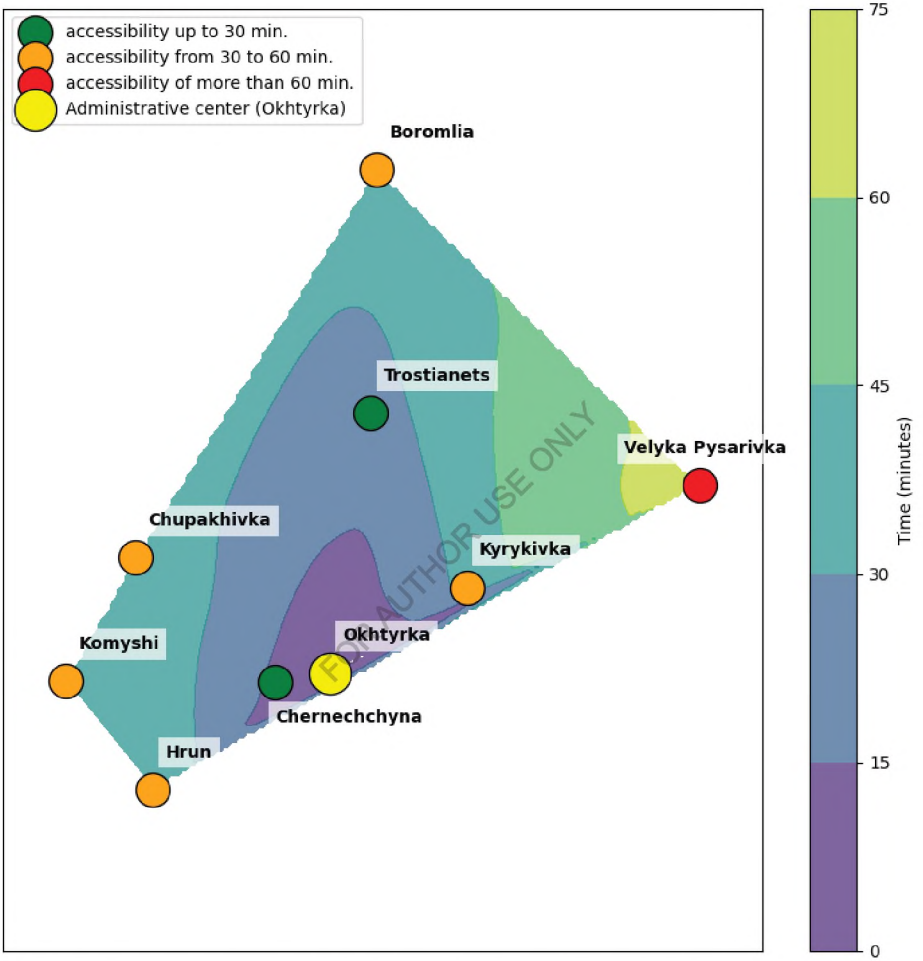


Fig 3. Isochrones (15-minute intervals) of automobile transport accessibility from territorial community centres to district centre – Okhtyrka (created in Matplotlib, visualised in Google Colab)

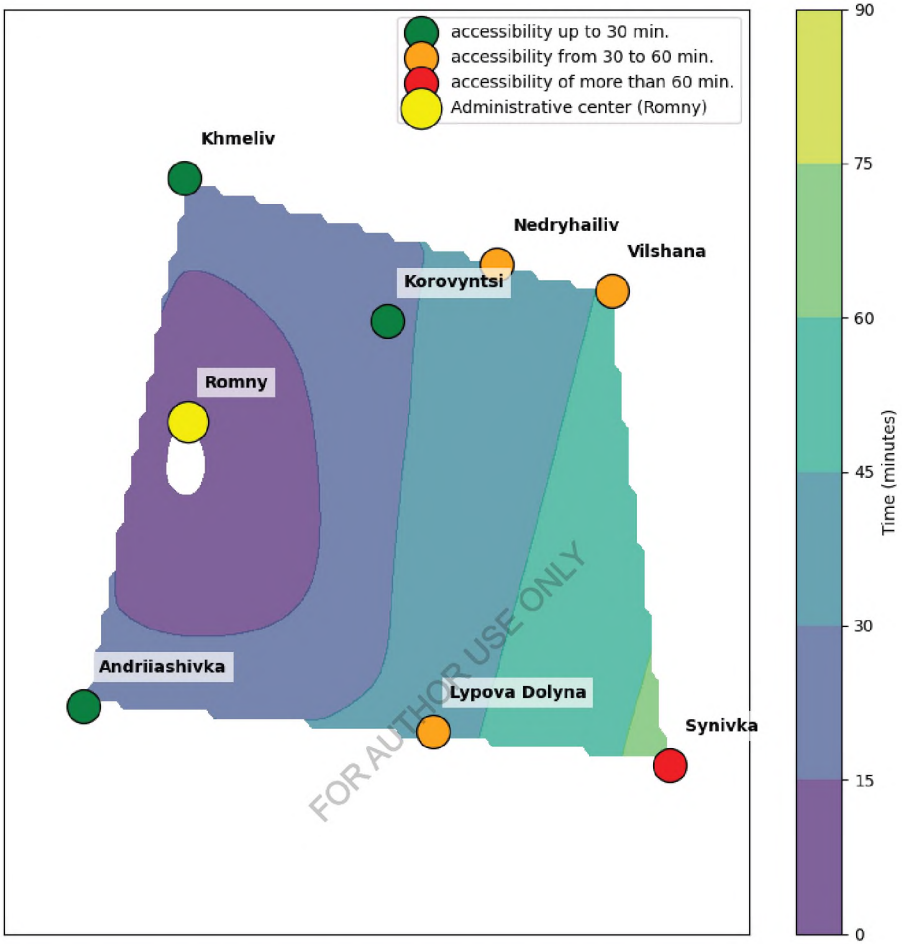


Fig. 4. Isochrones (15-minute intervals) of automobile transport accessibility from territorial community centres to district centre – Romny (created in Matplotlib, visualised in Google Colab)

Sumy District. Sumy District (Fig. 5) possesses the most developed and branched transport network in the region, largely due to the presence of the regional capital, Sumy, which functions as the principal transport hub. The proximity of numerous settlements to the regional centre results in high accessibility for many territorial community centres. In particular, Sad, Bezdryk, Verkhnia Syrovatka, and

Stepanivka fall within the 30-minute isochrone, ensuring rapid access to the administrative centre.

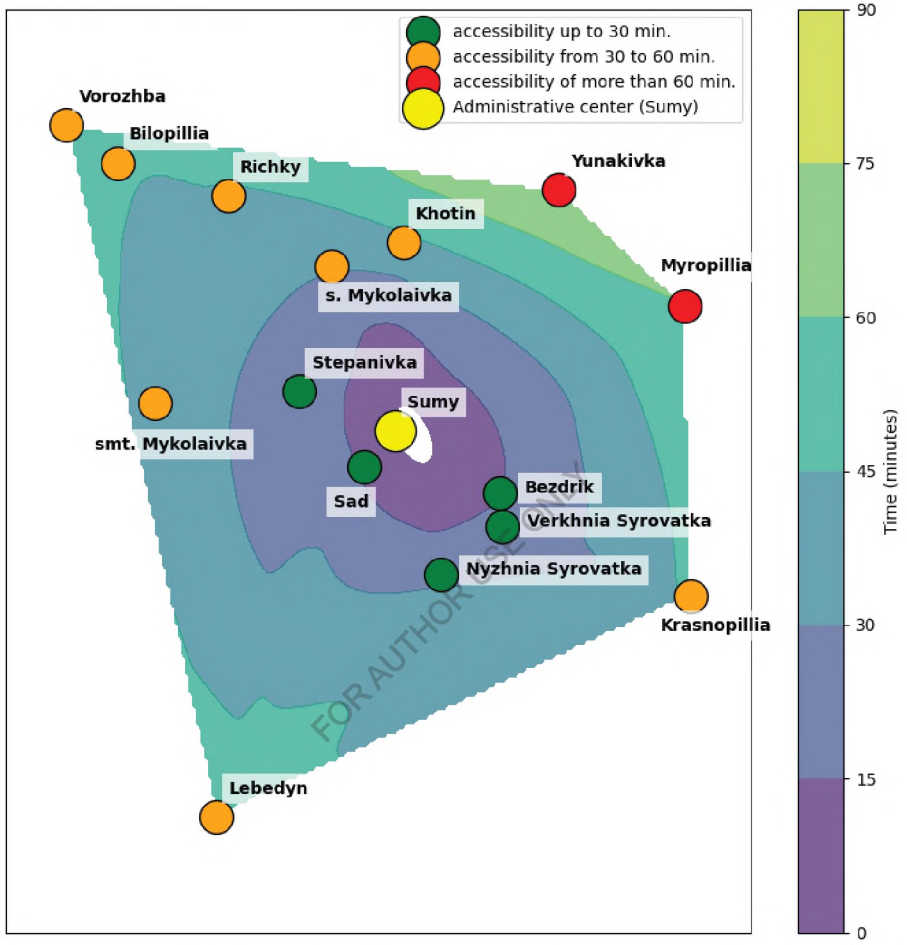


Fig. 5. Isochrones (15-minute intervals) of automobile transport accessibility from territorial community centres to district centre – Sumy (created in Matplotlib, visualised in Google Colab)

Despite the extensive spatial coverage of the 30-minute accessibility zone, several remote settlements, including Yunakivka, Vorozhba, and Myropillia, require more than 60 minutes to reach the district centre. This indicates their weaker integration into the regional transport network. Special attention should be given to Krasnopillia, which serves as the centre of a large territorial community and plays an important role

in cross-border logistics, further amplifying the strategic importance of its transport accessibility.

Shostka District. Shostka District is the most spatially elongated in Sumy Oblast, creating significant challenges for ensuring transport accessibility of peripheral communities to the district centre. Yampil and Bereza are located within the 30-45-minute accessibility zone, allowing for relatively high levels of mobility (Fig. 6).

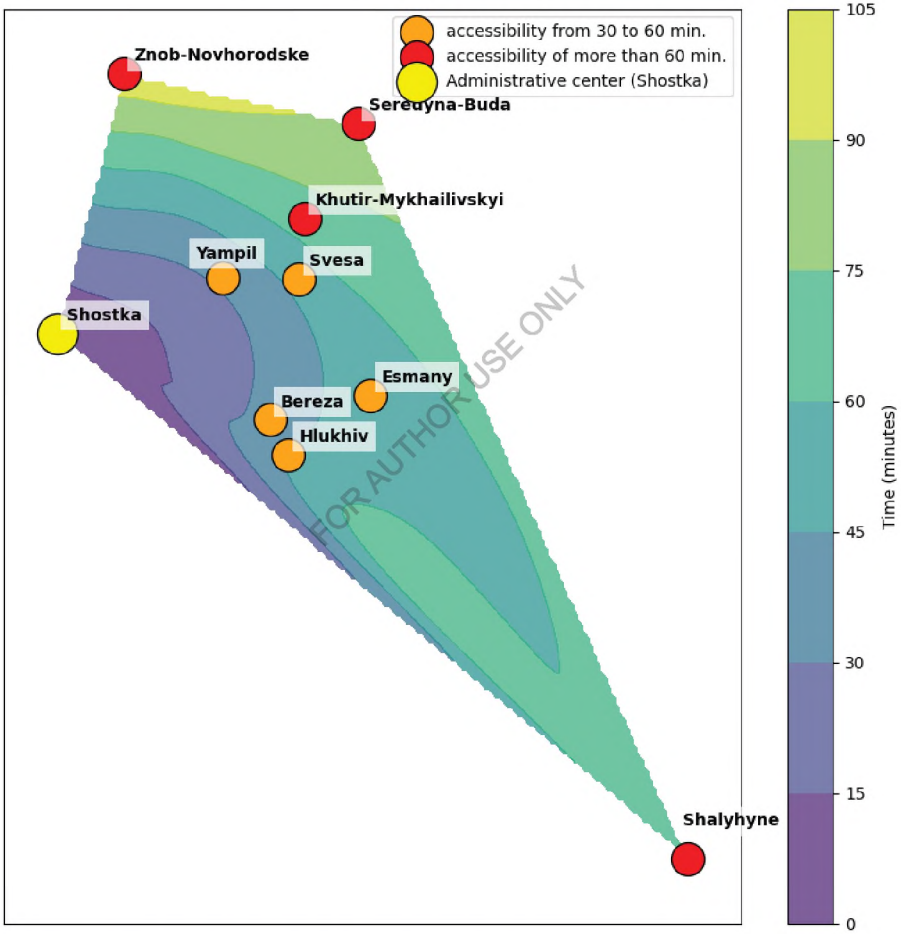


Fig. 6. Isochrones (15-minute intervals) of automobile transport accessibility from territorial community centres to district centre – Shostka (created in Matplotlib, visualised in Google Colab)

However, a substantial number of territorial community centres, including Seredyna-Buda, Znob-Novhorodske, and Khutir-Mykhailivskyi, require more than 60 minutes to reach the district centre. Special consideration should be given to Svesa, whose level of accessibility – taking into account the condition of the road network – requires improvement, given its role as an intermediate node facilitating access for residents of the Esman and Khutir-Mykhailivskyi territorial communities.

5.2. Interpretation of the Consistency between Network Centrality and Isochrone-Based Accessibility

The comparative analysis of network centrality measures and isochrone-based accessibility reveals a high degree of internal consistency between the structural properties of the transport network and the observed spatial patterns of travel-time accessibility in Sumy Oblast. The classification of territorial community centres into centrality classes demonstrates that the position of a node within the network topology strongly conditions its functional accessibility to district centres, as measured by isochrone zones.

FOR AUTHOR USE ONLY

At the upper end of the hierarchy, core transport hubs are characterised by a simultaneous concentration of high *Dc*, the highest values of *Cc*, and elevated *Bc*. These centres, most notably Sumy, occupy a structurally central position that minimises average travel distances to all other nodes and concentrates a substantial share of shortest paths. This structural dominance is directly reflected in the isochrone analysis: the majority of surrounding territorial community centres fall within the 30-minute accessibility zone. Such correspondence confirms that high network centrality translates into rapid and reliable access in real transport space, reinforcing the role of these centres as primary poles of regional mobility and service provision.

Secondary central hubs, such as Putyvl and Konotop, exhibit slightly lower degree centrality but retain high values of closeness and betweenness centrality, as well as elevated eigenvector centrality. This configuration indicates that, while these nodes may not possess the highest number of direct connections, they are embedded within strategically important corridors and are linked to other influential nodes. Isochrone

patterns corroborate this interpretation: these centres are predominantly associated with 30-45-minute accessibility zones, reflecting efficient but somewhat less immediate access compared to the oblast centre. Their role is therefore best understood as that of regional redistributors, facilitating inter-district connectivity and ensuring the continuity of transport flows across the northern and southern parts of the oblast.

A distinct category is formed by transit-oriented connector centres, which display moderate degree and closeness centrality values but relatively high betweenness centrality (typically $Bc \geq 0.10$). Nodes such as Krolevets, Lebedyn, Romny, and Shostka exemplify this group. From a topological perspective, their importance lies not in the number of connections or proximity to all other nodes, but in their function as intermediaries through which a disproportionate share of shortest paths passes. Isochrone analysis places these centres mainly within the 30-60-minute accessibility zones, underscoring their role as structurally important yet spatially intermediate nodes. The consistency between elevated betweenness centrality and intermediate isochrone zones highlights their vulnerability: disruptions at these locations would not necessarily isolate large areas immediately, but would significantly increase travel times and reduce network efficiency across multiple districts.

FOR AUTHOR USE ONLY

Balanced local centres occupy a middle position both structurally and spatially. These nodes exhibit moderate values across all centrality metrics, with no single measure dominating their profile. Their accessibility to district centres typically falls within the 45-60-minute isochrone zones. While they ensure acceptable levels of local mobility and serve as important service centres within their immediate hinterlands, their influence on regional-scale connectivity remains limited. The correspondence between their moderate centrality scores and intermediate isochrone zones supports the conclusion that these centres function primarily at the intra-district level rather than as regional transport nodes.

At the lower end of the hierarchy, peripheral but connected centres are characterised by low degree and closeness centrality values, near-zero betweenness centrality, and minimal eigenvector centrality. Communities such as Yunakivka, Kyrykivka, and Hrun fall into this category. Isochrone analysis consistently places

these centres within zones exceeding 60 minutes of travel time to district centres. This spatial pattern reflects their marginal structural position within the transport network, dependence on a limited number of routes, and weak integration into main transport corridors. The alignment between low centrality and extended isochrone zones underscores the cumulative disadvantages faced by peripheral communities in terms of accessibility and mobility.

Finally, structurally isolated nodes represent the most extreme manifestation of peripheralisation. These centres exhibit minimal connectivity, very low closeness centrality, and betweenness centrality values approaching zero, indicating that they neither serve as transit nodes nor benefit from proximity to central parts of the network. Isochrone zones exceeding 60 minutes, and in some cases approaching or surpassing 75 minutes, confirm their pronounced spatial isolation. Such centres are particularly vulnerable to further degradation of transport infrastructure and are at high risk of functional exclusion from regional systems of mobility and service access.

FOR AUTHOR USE ONLY

The Table 14 demonstrates a clear monotonic relationship between network centrality class and isochrone-based accessibility. As centrality values decrease across *Dc*, *Cc*, *Bc*, and *Ec* dimensions, territorial community centres systematically shift from compact ≤30-minute accessibility zones toward extended ≥60-minute isochrone zones. This confirms that structural position within the transport network is a primary determinant of real-world travel-time accessibility, while deviations are mainly attributable to road quality and natural barriers.

Overall, the strong correspondence between centrality classes and isochrone zones confirms that graph-theoretical measures provide a robust analytical framework for explaining observed patterns of transport accessibility. Deviations from this general trend can largely be attributed to non-topological factors, such as road quality, natural barriers (notably river crossings), and the spatial configuration of district centres. Nevertheless, the combined application of network centrality analysis and isochrone modelling allows for a comprehensive and nuanced assessment of transport accessibility, capturing both structural potential and realised travel-time constraints.

Table 14.

Relationship between network centrality classes and isochrone-based accessibility of territorial community centres in Sumy Oblast

Centrality class (*DC–CC–BC–EC* profile)	Typical centrality characteristics	Dominant isochrone zone (travel time to district centre)	Functional interpretation	Representative centres
I. Core transport hubs	Very high *Dc*, highest Cc, high *Bc* (≥ 0.30), moderate – high *Ec*	≤ 30 minutes	Primary accessibility cores; maximum connectivity and shortest average travel times; concentration of regional flows	Sumy
II. Secondary central hubs	High *Dc*, high *Cc* (> 0.25), high *Bc* (0.15-0.30), high *Ec*	30-45 minutes	Key regional transit nodes; ensure inter-district connectivity and redistribution of flows	Putyvl, Konotop
III. Transit-oriented connectors	Moderate *Dc*, moderate *Cc* (0.22 – 0.25), elevated *Bc* (≥ 0.10), moderate *Ec*	30-60 minutes	Structurally important intermediaries; potential bottlenecks; high sensitivity to disruptions	Krolevets, Lebedyn, Romny, Shostka
IV. Balanced local centres	Moderate *Dc* and *Cc*, low – moderate *Bc* (< 0.10), low – moderate *Ec*	45-60 minutes	Locally accessible but limited regional influence; support intra-district mobility	Trostianets, Okhtyrka, Bilopillia
V. Peripheral but connected centres	Low *Dc*, low *Cc* (< 0.20), near-zero *Bc*, very low *Ec*	≥ 60 minutes	Structurally marginal; dependent on few routes; limited accessibility and redundancy	Yunakivka, Kyrykivka, Hrun
VI. Structurally isolated nodes	Minimal *Dc*, very low *Cc*, *Bc* ≈ 0, negligible *Ec*	≥ 60 minutes (often > 75 min)	Extreme periphery; weakly integrated; vulnerable to isolation	Seredyna-Buda, Znob-Novgorodske

FOR AUTHOR USE ONLY

This integrated approach enhances the explanatory power of the analysis and provides a solid empirical basis for identifying priority areas for transport planning and infrastructure development in Sumy Oblast.

5.3. Policy and Planning Implications

The integrated analysis of transport network centrality measures and isochrone-based accessibility provides a robust empirical foundation for evidence-based transport and spatial planning in Sumy Oblast. By revealing the structural roles of individual community centres and their realised accessibility in travel-time space, this study offers concrete insights into how infrastructure investments, administrative decisions, and regional development strategies can be prioritised and spatially targeted.

5.3.1. Differentiated Planning Strategies Based on Centrality Classes. One of the key policy implications of this research is the necessity of abandoning uniform, one-size-fits-all approaches to transport development in favour of differentiated strategies aligned with the functional role of settlements within the transport network.

Core hubs, such as Sumy, which simultaneously exhibit the highest values of degree, closeness, and betweenness centrality, should be treated as system-critical nodes. Their high accessibility and concentration of transport flows imply that any degradation of infrastructure quality, traffic management inefficiencies, or security-related disruptions at these locations would have cascading negative effects across the entire region. From a planning perspective, this justifies prioritising these hubs for:

- preventive maintenance and resilience-oriented upgrades of road infrastructure;
- redundancy planning, including alternative bypass routes and multimodal integration;
- traffic flow optimisation to reduce congestion and improve reliability.

FOR AUTHOR USE ONLY

In contrast, secondary regional hubs such as Putyvl and Konotop require a different policy focus. Although they do not match the oblast centre in terms of absolute connectivity, their elevated betweenness and eigenvector centrality values indicate a disproportionate influence on network cohesion. Planning interventions in these centres should therefore prioritise safeguarding corridor functionality, particularly at river crossings, bridge infrastructure, and junctions where alternative routes are limited. Investments aimed at improving route quality through these nodes can yield region-wide benefits by reducing average travel times and increasing network robustness.

5.3.2. Managing Transit Nodes and Preventing Network Bottlenecks. The identification of transit-oriented centres with high betweenness centrality but moderate closeness centrality has direct implications for transport risk management. Settlements such as Krolevets, Lebedyn, Romny, and Shostka function as structural intermediaries that connect otherwise weakly linked parts of the network. While they may not always appear as top-priority locations based on simple accessibility metrics, their role as potential bottlenecks becomes evident through graph-theoretical analysis.

From a policy standpoint, this highlights the importance of:

- monitoring traffic volumes and infrastructure condition at these nodes;
- ensuring the availability of alternative routes or partial bypasses where feasible;
- integrating these centres into regional contingency planning, particularly in contexts of emergency response or infrastructure failure.

Failure to recognise the importance of such transit nodes may lead to underinvestment in strategically critical locations, thereby increasing the vulnerability of the entire transport system to local disruptions.

FOR AUTHOR USE ONLY

5.3.3. Addressing Peripheralization and Accessibility Inequalities. Perhaps the most socially significant implication of the analysis concerns peripheral and weakly integrated community centres. Nodes characterised by low degree, closeness, and betweenness centrality consistently correspond to isochrone zones exceeding 60 minutes of travel time to district centres. This persistent spatial disadvantage reflects not only geographical distance, but also structural marginalisation within the transport network.

From a regional development perspective, prolonged low accessibility can reinforce processes of socio-economic decline, population outmigration, and reduced access to public services. Policy responses in such areas should therefore be framed not merely in terms of efficiency, but also equity and territorial cohesion. Potential interventions include:

- targeted upgrading of critical access roads linking peripheral centres to the nearest transit hubs;

- improving road surface quality and speed consistency rather than constructing entirely new routes;
- integrating transport planning with service decentralisation strategies, reducing the necessity for frequent long-distance travel.

Importantly, the analysis suggests that improving a small number of strategically selected links may yield disproportionately large accessibility gains for peripheral communities, especially when these links connect to nodes with higher centrality.

5.3.4. Reconsidering the Role of District Centres in Spatial Planning. The comparison between centrality metrics and isochrone accessibility also calls for a nuanced reassessment of the role of district centres themselves. In several districts, district centres occupy excentric spatial positions and do not coincide with the most accessible or structurally central nodes within the district network. This misalignment may reduce the functional effectiveness of administrative centralisation and increase travel burdens for residents.

FOR AUTHOR USE ONLY

From a planning perspective, this raises important questions regarding:
- the spatial logic of administrative boundaries and service catchment areas;
- the potential need for polycentric service provision within districts;
- the strategic empowerment of sub-centres that exhibit high accessibility or transit significance despite lacking formal administrative status.

Rather than rigidly reinforcing existing administrative hierarchies, planners may benefit from recognising and utilising the de facto spatial logic revealed by transport network analysis.

5.3.5. Infrastructure Resilience and Strategic Redundancy. The combined use of centrality analysis and isochrone modelling highlights critical vulnerabilities related to network dependence on a limited number of high-impact nodes and corridors. Nodes such as Sumy and Putyvl emerge as both highly efficient and highly vulnerable: their disruption leads to significant increases in average path length and travel time across the network.

This finding underscores the importance of resilience-oriented planning, particularly in regions exposed to geopolitical, environmental, or infrastructural risks. Policy measures should therefore emphasise:

- the development of alternative routes that reduce over-reliance on single nodes;
- reinforcement of key bridges and river crossings that lack functional substitutes;
- scenario-based planning that evaluates the consequences of partial network failures.

Strategic redundancy should not be viewed as inefficiency, but rather as an investment in system stability and long-term sustainability.

5.3.6. Methodological Implications for Transport Planning Practice. Finally, this study demonstrates the practical value of integrating graph-theoretical metrics with isochrone-based accessibility analysis in applied transport planning. Centrality measures capture the structural potential of the network, while isochrones reflect the realised performance experienced by users. Their combined application allows planners to distinguish between:

- nodes that are structurally important but currently underperforming due to infrastructure quality;
- nodes that appear accessible locally but play a limited role in regional connectivity;
- locations where small-scale interventions could unlock significant system-wide benefits.

FOR AUTHOR USE ONLY

Institutionalising such integrated analytical approaches within regional planning practice would enhance the transparency, objectivity, and strategic focus of decision-making processes.

* * *

This chapter has demonstrated the analytical value of integrating network-based centrality measures with isochrone-based accessibility modelling for the assessment of transport systems at the regional level. By linking the structural properties of the transport network (degree, closeness, betweenness, and eigenvector centrality) with travel-time accessibility to district centres, the analysis moves beyond purely

topological interpretations and captures the functional performance of the network as experienced by users. This combined approach allows for a more comprehensive understanding of how spatial structure, infrastructure quality, and geographical constraints jointly shape transport accessibility in Sumy Oblast.

The results reveal a high degree of consistency between centrality-derived node hierarchies and isochrone-based accessibility zones, particularly for core and transit-oriented centres. Highly central nodes generally correspond to shorter travel times and larger 30-minute isochrone coverage, confirming their role as anchors of regional mobility. At the same time, important discrepancies were identified, especially in peripheral and border communities, where low accessibility persists despite moderate structural centrality or geographic proximity. These mismatches highlight the decisive influence of road quality, natural barriers, and network redundancy on realised accessibility, reinforcing the need to interpret centrality metrics in conjunction with travel-time modelling rather than in isolation.

FOR AUTHOR USE ONLY

Overall, Chapter 5 confirms that transport accessibility in Sumy Oblast follows a clearly differentiated, spatially structured pattern characterised by a highly accessible core, a belt of transit hubs, and a peripheral zone with systematically higher transport costs. The combined methodological framework applied in this chapter provides a robust basis for identifying priority areas for infrastructure investment, mitigating network vulnerabilities, and addressing territorial inequalities. In doing so, it establishes a direct analytical bridge between theoretical network analysis and practical transport and spatial planning, setting the stage for the general conclusions of the monograph.

Conclusions

This monograph has demonstrated that transport accessibility, when examined through a cartographic lens, constitutes a fundamentally spatial phenomenon that cannot be adequately captured by single indicators or purely descriptive approaches. By integrating network centrality measures with isochrone-based accessibility mapping, the study provides a comprehensive cartographic framework for analysing regional transport systems, revealing both their structural organisation and their functional performance. Using Sumy Oblast as empirical evidence, the research confirms that transport accessibility is shaped by the interaction of network topology, spatial configuration, and travel-time constraints, all of which must be interpreted through spatial visualisation and cartographic generalisation.

One of the key conclusions of this study is that network centrality metrics and isochrone-based accessibility represent complementary, rather than competing, perspectives on transport accessibility. Degree centrality (*Dc*) highlights nodes with a high number of direct connections, reflecting local connectivity and infrastructural density. Closeness centrality (*Cc*) captures overall transport efficiency by indicating how quickly a node can reach all other nodes within the network. Betweenness centrality (*Bc*), in turn, reveals the critical transit role of nodes that structure regional flows and whose disruption would disproportionately affect network cohesion. When mapped and interpreted cartographically, these measures allow the identification of core nodes, transit corridors, and peripheral zones with a level of clarity that cannot be achieved through numerical analysis alone.

FOR AUTHOR USE ONLY

The case of Sumy Oblast clearly illustrates a polycentric but hierarchically structured regional transport system. Sumy emerges as the dominant core node across all centrality dimensions, combining the highest degree, closeness, and betweenness values, and occupying the most favourable position in isochrone-based accessibility maps. This confirms its role not only as an administrative centre, but also as the principal spatial organiser of regional mobility. At the same time, other centres such as Putyvl and Konotop demonstrate high strategic importance, particularly in terms of

betweenness and eigenvector influence, functioning as critical connectors between northern and southern parts of the region and compensating for natural barriers such as the Seim River. These findings underline that regional accessibility is not determined solely by the size or administrative status of settlements, but by their structural position within the transport network.

The isochrone analysis adds an essential temporal dimension to the cartographic interpretation of accessibility. While centrality measures reveal the structural importance of nodes, isochrone maps show how this importance translates into real travel-time conditions for territorial community centres. The comparison of centrality classes with isochrone zones demonstrates a high degree of consistency for core and transit nodes, but also exposes important mismatches. Several communities with moderate or even low network centrality are located within favourable isochrone zones due to high-quality roads or proximity to major corridors, whereas some structurally important nodes remain constrained by peripheral location, poor infrastructure, or limited crossing points. This reinforces the conclusion that transport accessibility is a multidimensional spatial property, requiring both network-based and time-based cartographic representations.

FOR AUTHOR USE ONLY

A particularly important outcome of the research is the identification of structural vulnerabilities and potential bottlenecks within the regional transport system. Nodes with high betweenness centrality, such as Sumy and Putyvl, simultaneously represent points of efficiency and points of risk. Their cartographic depiction as dominant transit hubs highlights the concentration of flows and the limited availability of alternative routes. The simulated removal of such nodes, reflected in increased average path lengths, demonstrates the sensitivity of regional accessibility to disruptions at specific locations. From a cartographic perspective, this finding emphasises the value of network-based maps as tools not only for description, but also for scenario analysis and resilience assessment.

At the opposite end of the accessibility spectrum, the study identifies a set of peripheral communities characterised by low degree, closeness, and betweenness centrality, combined with unfavourable isochrone positions. Settlements such as Hrun,

Kyrykivka, and Yunakivka illustrate the cumulative effect of sparse connectivity, peripheral location, and infrastructural limitations. Cartographically, these areas form clearly distinguishable zones of reduced accessibility, which correspond to increased travel times, weaker integration into regional flows, and heightened risks of socio-economic marginalisation. The spatial coherence of these peripheral zones confirms the explanatory power of cartographic synthesis in revealing patterns of inequality within regional transport systems.

From a methodological standpoint, the monograph demonstrates that cartography is not merely a tool for visualising results, but a core analytical framework for transport accessibility research. The combination of graph-based metrics with isochrone mapping enables multi-scale analysis, from individual nodes to entire regional systems, and supports the identification of spatial regularities, anomalies, and thresholds. The use of normalised centrality values ensures comparability, while the cartographic representation of right-skewed distributions highlights the dominance of a small number of structurally critical nodes. This approach reinforces the role of cartography as a means of spatial reasoning, rather than simple illustration.

FOR AUTHOR USE ONLY

The findings of this study have clear implications for regional planning and transport policy. The cartographic identification of core nodes, transit hubs, and bottlenecks provides a spatially explicit basis for prioritising infrastructure investments, improving redundancy in critical corridors, and addressing accessibility deficits in peripheral communities. Isochrone maps, when interpreted alongside centrality measures, offer an intuitive and policy-relevant representation of accessibility outcomes, making them particularly suitable for communication with decision-makers and stakeholders. Importantly, the results suggest that targeted interventions at a limited number of strategically positioned nodes may yield disproportionately large improvements in overall regional accessibility.

In a broader disciplinary context, this monograph contributes to the development of transport cartography as an integrative field at the intersection of geography, GIS-science, and network analysis. By explicitly linking network centrality measures with isochrone-based mapping, it advances a coherent methodological framework that can

be transferred to other regions and transport systems. While the empirical evidence is drawn from Sumy Oblast, the conceptual and cartographic principles developed in this study are applicable to a wide range of regional contexts, particularly in peripheral or border regions with uneven infrastructure development.

In conclusion, the research confirms that effective analysis of transport accessibility requires a cartographic synthesis of network structure and travel-time space. The proposed approach allows not only the assessment of current accessibility patterns, but also the identification of vulnerabilities, planning priorities, and pathways for improving spatial equity. By positioning cartography at the centre of transport accessibility analysis, this monograph demonstrates its enduring relevance as both an analytical science and a practical tool for understanding and shaping regional systems.

FOR AUTHOR USE ONLY

REFERENCES

1. Pidhrushnyi, H. P., Nahirna, V. P., Fashchevskyi, M. I., Horlenko, I. O., Kachayev, Y. D., Savchuk, I. H., Yasniuk, T. Ye., Dubin, V. H., Shabashova, L. Yu., Denysenko, O. O., Pashynska, N. M., Nemchenko, M. P., Sereda, N. I., Bondar, V. V., Demianenko, T. V., Volovyk, L. M., & Isychenko, I. V. (2012). Integral potential of the territory: Theoretical and practical aspects of research [Monograph]. Institute of Geography, National Academy of Sciences of Ukraine, 464. [in Ukrainian].

2. Hansen, W. G. (1959). How Accessibility Shapes Land Use. Journal of the American Institute of Planners, 25(2), 73-76. https://doi.org/10.1080/01944365908978307

3. Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. Journal of Transport Geography, 12(2), 127-140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

4. Preston, J. & Rajé, F. (2007). Accessibility, mobility and transport-related social exclusion. Journal of Transport Geography, 15(3), 151-160. https://doi.org/10.1016/j.jtrangeo.2006.05.002

5. Apparicio, P., Abdelmajid, M., Riva, M., & Shearmur, R. (2008). Comparing alternative approaches to measuring the geographical accessibility of urban health services: Distance types and aggregation-error issues. International Journal of Health Geographics, 7(7). https://doi.org/10.1186/1476-072X-7-7

6. Apparicio, P., Gelb, J., Dubé, A.-S., Kingham, S., Gauvin, L., & Robitaille, É. (2017). The approaches to measuring the potential spatial access to urban health services revisited: Distance types and aggregation-error issues. International Journal of Health Geographics, 16(32). https://doi.org/10.1186/s12942-017-0105-9

7. Porta, S., Latora, V., & Crucitti, P. (2006). The network analysis of urban streets: A primal approach. Environment and Planning B: Planning and Design, 33(5), 705-725. https://doi.org/10.1068/b32045

8. Blanchard, S. D., & Waddell, P. (2017). UrbanAccess: Generalized Methodology for Measuring Regional Accessibility with an Integrated Pedestrian and Transit Network. Transportation Research Record: Journal of the Transportation Research Board, 2653(1), 35-44. https://doi.org/10.3141/2653-05

9. Park, J., & Goldberg, D. W. (2021). A review of recent spatial accessibility studies that benefitted from advanced geospatial information: Multimodal transportation and spatiotemporal disaggregation. ISPRS International Journal of Geo-Information, 10(8), Article 532. https://doi.org/10.3390/ijgi10080532

FOR AUTHOR USE ONLY

10. Büttner, B., Kinigadner, J., Ji, C., Wright, B., & Wulfhorst, G. (2018). The TUM Accessibility Atlas: Visualizing spatial and socioeconomic disparities in accessibility to support regional land-use and transport planning. Networks and Spatial Economics, 18(2), 385-414. https://doi.org/10.1007/s11067-017-9378-6

11. Poudyal, B., Ghoshal, G., & Kirkley, A. (2023). Characterizing network circuity among heterogeneous urban amenities. Journal of the Royal Society Interface, 20, Article 20230296. https://doi.org/10.1098/rsif.2023.0296

12. Hashtarkhani, S., Schwartz, D. L., & Shaban-Nejad, A. (2024). Enhancing health care accessibility and equity through a geoprocessing toolbox for spatial accessibility analysis: Development and case study. JMIR Formative Research, 8, e51727. https://doi.org/10.2196/51727

13. Condeço-Melhorado, A., Reggiani, A., & Gutiérrez, J. (2018). New data and methods in accessibility analysis. Networks and Spatial Economics, 18, 237-240. https://doi.org/10.1007/s11067-018-9404-3

14. Salze, P., Banos, A., Oppert, J.-M., et al. (2011). Estimating spatial accessibility to facilities on the regional scale: An extended commuting-based interaction potential model. International Journal of Health Geographics, 10, Article 2. https://doi.org/10.1186/1476-072X-10-2

15. Puhach, S. O., & Novosad, S. V. (2015). Interpretation of the concepts of "transport accessibility" and "space-time compression" in modern scientific literature. In *Current issues of regional studies* (Proceedings of the 3rd International scientific and practical Internet conference, Lutsk, December 15-16, 2015, pp. 28-31). Lutsk, Ukraine: Vezha [in Ukrainian].

16. Mazurova, A. V., & Virchenko, P. A. (2012). Socio-geographical factors causing transport discrimination of the population of Ukraine (a case study of railway transport). In *Region-2012: Strategy of optimal development* (Proceedings of the international scientific and practical conference, pp. 144-147). Kharkiv, Ukraine: V. N. Karazin Kharkiv National University [in Ukrainian].

17. Anisimova, S. V., Vasenko, O. H., & Anisimov, S. V. (2017). Assessment of transport accessibility of suburban recreation areas as a factor influencing the recreational value of a territory. *Automobile Transport*, 41, 196-203. https://doi.org/10.30977/AT.2219-8342.2017.41.0.196 [in Ukrainian].

18. Anisimov, S. V. (2017). Territorial and transport accessibility of suburban recreational areas for summer recreation. *Man and Environment. Issues of Neoecology*, 3-4, 95-104 [in Ukrainian].

19. Baiteriakov, O. Z., & Voronova, V. V. (2024). Topological analysis of the road transport network of Zaporizhzhia Oblast. *Visnyk of V. N. Karazin Kharkiv National University. Series: Geology. Geography. Ecology*, 60, 137-158. https://doi.org/10.26565/2410- [in Ukrainian].

FOR AUTHOR USE ONLY

20. Barskyi, Yu. M., Puhach, S. O., & Yakovlev, T. V. (2016). Spatial analysis of transport accessibility of territories within the city of Lutsk. *Economic Sciences. Series: Regional Economics*, 13, 35-45 [in Ukrainian]

21. Dziubynska, O. V., Dziubynskyi, A. V., & Smal, M. V. (2014). Assessment of transport accessibility of recreational areas of Volyn Oblast. *Economic Sciences. Series: Regional Economics*, 11, 95-101 [in Ukrainian].

22. Zahurskyi, O. M. (2018). Transport accessibility of rural areas: Methodological approaches. *Automobile Transport*, 43, 65-70. https://doi.org/10.30977/AT.2219-8342.2018.43.0.65 [in Ukrainian].

23. Zauralska, A. V. (2013). Determining transport accessibility of sports infrastructure objects using the example of training bases of football clubs. *Urban Planning and Territorial Planning*, *(48)*, 179-184 [in Ukrainian].

24. Leiberiuk, O. M. (2017). Transport accessibility of the population to hospital district centers (a case study of Chernivtsi Oblast). *Scientific Bulletin of Kherson State University. Series: Geographical Sciences*, (7), 62-68 [in Ukrainian].

25. Matiichyk, O.M. (2017). Efektyvnist dostupnosti transportnoi merezhi na prykladi Stolychnoho ekonomichnoho raionu [Effectiveness of transport network accessibility on the example of the Capital Economic Region]. *Molodyi vchenyi*, 4, 552-555 [in Ukrainian].

26. Matiichyk, O.M. (2017). Teoretychni aspekty realizatsii transportnoi dostupnosti pasazhyrskykh transportnykh system [Theoretical aspects of transport accessibility implementation in passenger transport systems]. *Molodyi vchenyi*, 9, 467-470 [in Ukrainian].

27. Mykhailov, A. V. (2012). Average distance of urban areas and population of Donetsk city relative to the city center considering transport accessibility. *Urban Development and Territorial Planning*, *45*(2), 24-28 [in Ukrainian]

28. Silchenko, Yu. Yu., Semeniuk, L. L., & Zarubina, A. V. (2017). Analysis of the impact of transport accessibility on the socio-economic development of the Kirovohrad region. *Scientific Bulletin of Kherson State University. Series: Geographical Sciences*, *7*, 81-87 [in Ukrainian]

29. Tomashchuk, M. M. (2018). Possibilities of geoinformation analysis in studies of transport accessibility of potential administrative centers of united territorial communities. *Engineering Geodesy*, 65, 126-135 [in Ukrainian].

30. Tretiak, V. M., & Lepetiuk, V. B. (2021). Determination of transport accessibility in the formation of tourist routes using QGIS and GRASS GIS. *Urban Development and Territorial Planning*, *76*, 297-307. https://doi.org/10.32347/2076-815x.2021.76.297-307 [in Ukrainian].

31. Ul, A. V., Melnyk, O. V., Melnyk, Yu. A., & Synii, S. V. (2019). Geoinformation modeling of transport accessibility of territories. *Modern Technologies and Methods of Calculations*

FOR AUTHOR USE ONLY

in Construction, 12, 213-220. https://doi.org/10.36910/6775-2410-6208-2019-2(12)-26 [in Ukrainian].

32. Yanovskyi, P. O., & Matiichyk, O. M. (2013). Assessment of passenger transport accessibility at the regional level. *Science-Intensive Technologies*, 3, 345-348 [in Ukrainian].

33. Kornus, A. O. (2025). Cartographic and geographical analysis of transport accessibility of community centers in Sumy Oblast based on graph theory. In Djakons, R., Kornus, A. O., Danylychenko, O. S., & Kornus, O. H. (Eds.), *Earth Sciences, Geography, and Cartography: Regional Studies and Spatial Analysis:* Scientific Monograph (pp. 291-314). Riga: Baltija Publishing. https://doi.org/10.30525/978-9934-26-596-9-14 [in Ukrainian].

34. Kornus, A. O., Kornus, O. H., Danylychenko, O. S., Korol, O. M., & Lutsenko, S. V. (2025). Transport accessibility of administrative centers of Sumy Oblast: A spatial-geographical approach. *Sloboda Scientific Journal. Series: Natural Sciences*, 2, 109-115. https://doi.org/10.32782/naturalspu/2025.2.14 [in Ukrainian].

35. Kornus, A., & Kornus, O. (2025). Cartographic modeling of transport accessibility of the centers of territorial communities in Sumy Oblast. *Human Geography Journal*, (38), 50-57. https://doi.org/10.26565/2076-1333-2025-38-06

36. Bavelas, A. (1950). Communication patterns in task-oriented groups. *The Journal of the Acoustical Society of Americ*a, 22(6), 725-730. https://doi.org/10.1121/1.1906679

37. Beauchamp, M. A. (1965). An improved index of centrality. *Systems Research*, 10, 161-163. https://doi.org/10.1002/bs.3830100205

38. Ukrstat. (2025). *State Statistics Service of Ukraine*. URL: https://stat.gov.ua/en

FOR AUTHOR USE ONLY

KORNUS Anatolii

CARTOGRAPHIC MODELLING OF SETTLEMENT TRANSPORT ACCESSIBILITY

Graph-Based Centrality Analysis and Time-Based Isochrone Mapping of Territorial Communities in Sumy Oblast, Ukraine

Monograph

FOR AUTHOR USE ONLY

Format: 148 x 210 mm. **Typeface:** Times New Roman. **Conv. print sheets:** 6.1.

FOR AUTHOR USE ONLY

More Books!



yes

I want morebooks!

Buy your books fast and straightforward online - at one of world's fastest growing online book stores! Environmentally sound due to Print-on-Demand technologies.

Buy your books online at
www.morebooks.shop

Kaufen Sie Ihre Bücher schnell und unkompliziert online – auf einer der am schnellsten wachsenden Buchhandelsplattformen weltweit! Dank Print-On-Demand umwelt- und ressourcenschonend produziert.

Bücher schneller online kaufen
www.morebooks.shop

info@omniscriptum.com
www.omniscriptum.com

OMNIScriptum

FOR AUTHOR USE ONLY

This monograph presents a cartographic analysis of settlement transport accessibility based on graph theory and isochrone modelling, using Sumy Oblast (Ukraine) as a regional case study. The research integrates network centrality measures with time-based accessibility mapping to identify spatial inequalities, structural hierarchies, and the functional roles of territorial community centres. Transport accessibility is examined through a multi-method framework combining graph topology, connectivity characteristics, and centrality metrics (degree, closeness, betweenness, and eigenvector centrality). Isochrone mapping of automobile travel times to district centres enables direct comparison between structural network centrality and actual accessibility conditions. The results reveal a differentiated spatial structure of the transport network, including a highly integrated core, a system of transit nodes, and peripheral areas with limited accessibility. Special attention is given to transit centres and potential bottlenecks, as well as to cases where network centrality does not correspond to isochrone accessibility, highlighting key methodological limitations.



Anatolii Kornus is a Ukrainian geographer and cartography researcher specialising in regional spatial analysis. He has authored scholarly publications on transport accessibility, regional spatial structure, and applied cartography, and has contributed to research and educational projects in the field of sustainable regional development.

9 786209 479694