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Research Article

GIS-based spatial analysis of transportation accessibility to emergency medical services: A case study of Smolyan district, Bulgaria

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Abstract

Spatial accessibility of healthcare facilities may result in substantial differences in the population's access to medical care. This is a topic of great public importance that needs effective planning based on contemporary spatial technologies and analytical approaches. The aim of the present study is to demonstrate how the application of spatial analyses, tailored to the specific context, contributes to identifying gaps in the existing organization of emergency medical services in mountainous areas and enables a more comprehensive and robust assessment of transport accessibility. By integrating three complementary analytical approaches—Service Area, Closest Facility, and Origin–Destination Cost Matrix analyses within a single methodological framework, the present study provides a comprehensive assessment of travel times from emergency medical care branches to the settlements they serve, as well as an evaluation of branch service areas in terms of their spatial extent. The analyses identified shortcomings that could be addressed with reorganization and low-cost optimization measures, thus demonstrating their efficiency in identifying limitations in the current allocation of service areas among the emergency medical care branches. The study is based on carefully selected data and was conducted with a strong emphasis on maximizing both accuracy and practical applicability.

Key words: Closest facility, emergency medical care, network analysis, origin-destination cost matrix, service area, transport accessibility

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1. Introduction

Ensuring equitable access to healthcare services is one of the major challenges facing contemporary healthcare systems. In scientific literature, access to healthcare is regarded as a multidimensional concept encompassing economic, organizational, and spatial dimensions (Guagliardo 2004). Among these, spatial accessibility occupies a central role, as it reflects the ability of the population to reach healthcare facilities depending on their location and the characteristics of the transportation network. Spatial accessibility is most commonly

assessed using indicators related to travel distance and travel time. The development of Geographic Information Systems (GIS) and spatial analytical methods has substantially expanded the possibilities for accessibility research by facilitating the assessment of spatial disparities in healthcare provision and supporting the planning and allocation of healthcare resources (Ray and Ebener 2008; Wood et al. 2023).

The spatial distribution of healthcare facilities and the characteristics of the transportation network may result in substantial differences in the population's access to medical care. In areas characterized by rugged terrain, dispersed settlement patterns, or limited transport connectivity, reaching a healthcare facility often requires considerably more travel time than in areas with more favourable geographical and infrastructural conditions. For this reason, travel time is widely regarded as one of the most appropriate indicators for assessing spatial accessibility, as it reflects actual travel conditions within the road network more accurately than straight-line distance measurements (Fone et al. 2006; Delamater et al. 2012). Consequently, travel time-based indicators have been widely adopted in studies of spatial accessibility and form the basis of the present analysis.

The widespread application of GIS and network analysis has created new opportunities for investigating spatial accessibility to healthcare services. By incorporating real-world transportation networks, it is possible to evaluate travel times to healthcare facilities, delineate service areas, and identify disparities in accessibility among individual settlements. Such approaches have been widely applied in studies aimed at assessing healthcare accessibility and identifying areas with less favourable service provision (Isaacson et al. 2021; Zhao and Zhou 2024; Cazacu et al. 2025). The resulting findings provide valuable evidence to support the planning and optimization of healthcare infrastructure.

Spatial disparities in transport accessibility to healthcare services are particularly pronounced in regions characterized by complex physical geographical conditions. Mountainous terrain, limited transport connectivity, and the presence of small, dispersed settlements can have a substantial impact on travel times to healthcare facilities. In such areas, even relatively short distances are often associated with considerably longer travel times, resulting in unequal levels of service accessibility for the population. Consequently, assessing spatial accessibility in mountainous regions represents an important tool for identifying settlements with limited access to healthcare services and for supporting territorial planning and the effective management of healthcare infrastructure.

The present study investigates the transport accessibility from Emergency Medical Care Branches (EMCBs) to the settlements they serve by applying a combination of GIS-based network analysis techniques.

Although studies of this type have been conducted in Bulgaria, they remain limited in number and provide a less in-depth assessment of transport accessibility. To the best of the authors knowledge, this is the first study in Bulgaria to integrate three complementary analytical approaches—Service Area, Closest Facility, and Origin–Destination (OD) Cost Matrix analyses within a single methodological framework. This integrated approach enables both the assessment of travel times from emergency medical care branches to the settlements they serve and the evaluation of branch service areas in terms of their spatial extent, thereby providing a comprehensive basis for optimizing the organization of the emergency medical care system within the study area.

Each of these analytical approaches has been widely applied in previous studies, although they have generally been used independently rather than in combination. Service Area analysis has been employed extensively in transport accessibility research (Xia et al. 2019; Luo et al. 2020; Isaacson et al. 2021; Xiong et al. 2022; Nikolova and Patarchanova 2024; Zhao and Zhou 2024; Zhang et al. 2024; Popescu and Bărbulescu 2025). In some of these studies, Service Area analysis is explicitly described as a core component of the methodological framework, whereas in the studies by Xiong et al. (2022), Luo et al. (2020), and Xia et al. (2019), its application can only be inferred from the reported results.

Origin-Destination (OD) Cost Matrix analysis also constitutes an important component of the methodological framework in numerous studies (Delamater et al. 2012; Zhou et al. 2020; Isaacson et al. 2021; Wood et al. 2023; Zhao and Zhou 2024). This approach is particularly well suited to regional-scale analyses, as it enables the estimation of travel times from service facilities—in the present study, from the EMCBs to the settlements within their service areas. By comparison, fewer published studies have employed Closest Facility analysis (Nicoară and Haidu 2014; Isaacson et al. 2021).

By employing this integrated approach, the present study explores the application of GIS and spatial analyses in a very specific topic of essential public importance and demonstrates how they play a pivotal role in identifying deficiencies in the current allocation of service areas among the emergency medical care branches. The aim of the present study is to demonstrate how the application of spatial analyses, tailored to the specific context, contributes to identifying gaps in the existing organization of emergency medical services in mountainous areas and enables a more comprehensive and robust assessment of transport accessibility. The following research questions guide this study: (i) is the existing spatial organization well adapted to the terrain characteristics and population density? (ii) how accurate are the GIS analyses against the most widely used routing and navigation platforms? (iii) what are the practical applications of this kind of integrated approaches especially for suggesting alternatives. The study is based on carefully selected data and was conducted with a strong emphasis on maximizing both accuracy and practical applicability.

2. Materials and methods

2.1. Case study area

The territory served by the Center for Emergency Medical Care in Smolyan (CEMC Smolyan) and its Emergency Medical Care Branches (EMCBs) was selected as the study area. According to the National Health Map (Ministry of Health 2026a), this territory fully coincides with the administrative boundaries of Smolyan District. Owing to its highly dissected mountainous terrain, the region is considered one of the most challenging areas in Bulgaria in terms of transport accessibility to emergency medical care services.

The territory of Smolyan District comprises ten municipalities that are covered by nine EMCBs (Fig. 1). Among them, only the service area of the Dospat branch coincides with the administrative boundaries of the municipality in which it is located. The Devin branch is responsible for providing emergency

medical care services to the municipalities of Devin and Borino, making it the second-largest branch in terms of service area. Consequently, its catchment area includes 23 settlements.

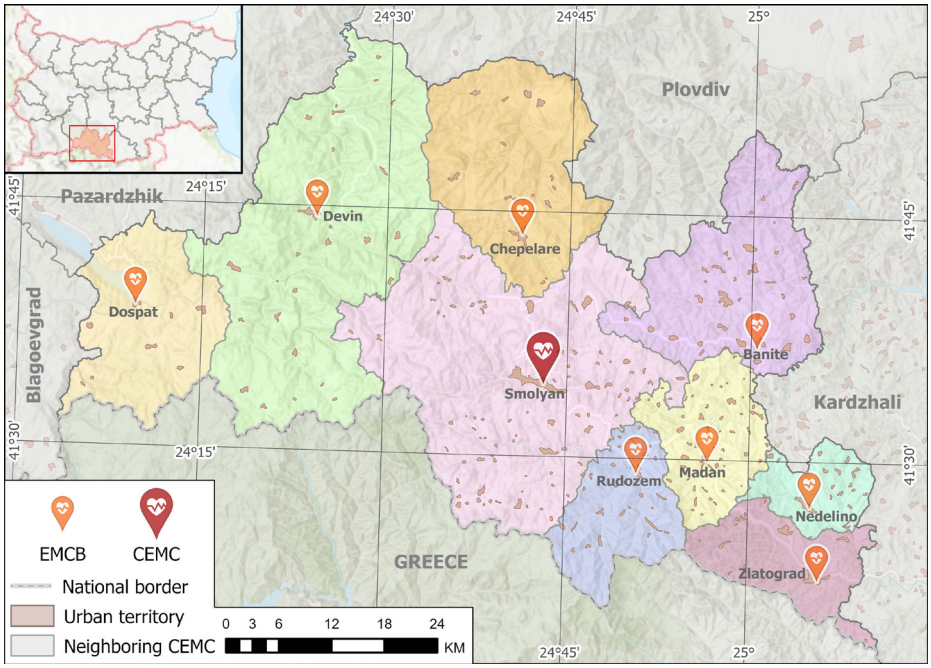

Figure 1. Study area and Emergency Medical Care branches.

An even greater number of settlements fall within the service area of the largest branch by territory, namely the branch located in Smolyan. It serves a total of 83 settlements, including the district center, which, due to its relatively high population concentration, generates a greater potential demand for emergency medical care services.

The larger service areas of these two branches, combined with the highly dissected mountainous terrain and the resulting lower road network density and lower average travel speeds, create conditions for less favourable levels of transport accessibility. These factors are also relevant to the remaining branches within the province; however, owing to their smaller service areas, the problem is less pronounced.

Several key factors influence the results of transport accessibility analyses. The first of these is the terrain, which has already been mentioned on several occasions. Smolyan Province encompasses part of the Western Rhodope Mountains, characterized by pronounced vertical and horizontal dissection. Narrow river valleys and gorges are typical of the region, and a considerable proportion of the road infrastructure is concentrated along these landforms. In addition, the province lacks vast valley fields and plains that would allow the development of a denser road network. These characteristics primarily affect the results obtained through Service Area analysis.

Road infrastructure also plays a significant role in determining transport accessibility. As shown in Fig. 2, the density of the road network within the province is considerably higher in its eastern parts, particularly within the catchment areas of the Rudozem and Madan branches, as well as in the eastern sections

of the Smolyan branch catchment area. These territories are also characterized by a higher density of the settlement network.

Regarding road classification, the national road network within the province consists of second-class roads (Road II-86 and Road II-37) and segments of 18 third-class roads. Owing to the rugged mountainous terrain, the roads in the province are characterized by numerous curves and relatively low average travel speeds.

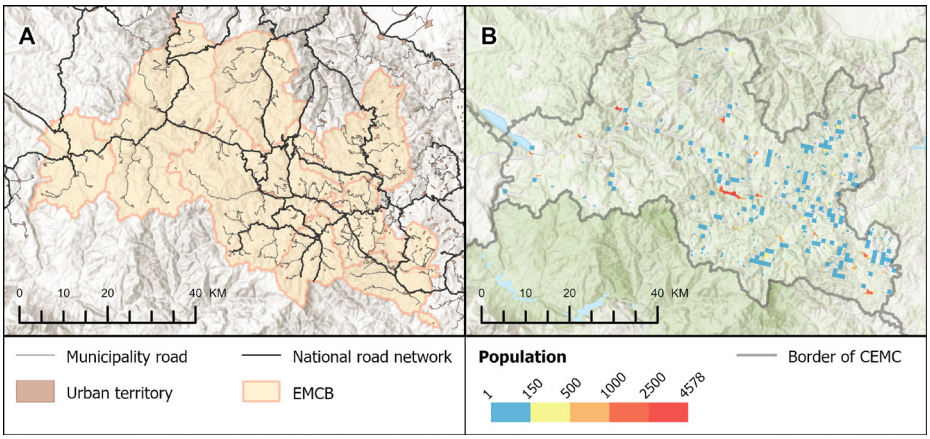

Figure 2. Smolyan district. **A** roads **B** population density.

When analyzing transport accessibility to critical services, the most important indicator to be considered is the proportion of the population covered within the predefined accessibility isochrones. In this context, the spatial distribution of the population across the study area is of paramount importance. The analysis incorporates population data for 248 compact urbanized areas, including the Pamporovo resort complex (where no permanent population has been recorded) and 14 settlements that, according to the National Register of Settlements (NSI 2026), have no permanent residents.

A distinctive characteristic of Smolyan Province is the high concentration of population in the settlements where the emergency medical care branches are located, accounting for 57.79% of the total population (slightly more than 52,000 inhabitants). This provides favourable conditions for achieving a high level of population coverage within the most advantageous travel time interval. At the same time, the remainder of the population is widely dispersed across the district. More than half of all settlements (135) have fewer than 100 inhabitants, while 49 settlements have populations even below ten inhabitants.

The significance of the present study is further emphasized by the overall distribution of healthcare resources within the region. Eight healthcare facilities operate within the study area, of which only four are multiprofile hospitals for active treatment (Fig. 3). Of the remaining facilities, three are specialized rehabilitation hospitals, and one is a mental health center. Fig. 3 clearly shows a higher concentration of multiprofile hospitals for active treatment in the eastern half of the region, while only one hospital—the hospital in Devin—is located in its western part.

It should also be noted that the hospitals in Devin, Madan, and Zlatograd are accredited at the lowest level of competence for the medical specialties they provide, whereas the hospital in Smolyan is accredited at the intermediate,

second level for most of its medical activities. It is also the only hospital in the region providing emergency medicine, gastroenterology, urology, and ophthalmology, as well as services in transfusion hematology and dialysis, and laboratory services in microbiology and tuberculosis.

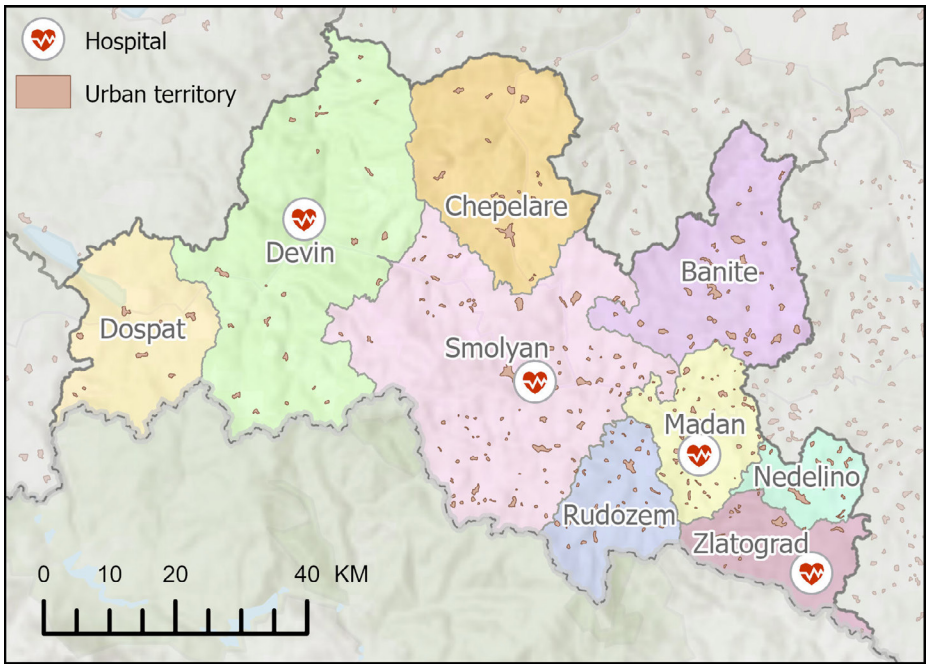

Figure 3. Hospitals in Smolyan district.

This strong concentration of higher-level specialized medical services in the regional center further emphasizes the importance of an appropriate spatial distribution of emergency medical care structures across the region and of ensuring high levels of transport accessibility to their services.

2.2. Data

A geodatabase of the emergency medical care system was developed to support the network analyses. The locations of the emergency medical care branches were digitized based on information published on the website of the Center for Emergency Medical Care (CEMC Smolyan 2026) and in the National Health Map. The addresses were subsequently verified using Google Maps, Google Street View, and BGMaps. Owing to the specific characteristics of these facilities and the insufficient positional accuracy of available online datasets, existing online spatial data sources were not used.

The National Health Map (Ministry of Health 2026a) was also used to delineate the catchment areas of the emergency medical care branches. This document (Appendix No. 35 to Section I, Subsection 8) contains a list of the Centers for Emergency Medical Care, their branches, and the settlements served by each branch. To create a data layer representing branch catchment areas, boundaries of the settlements land were used and subsequently merged according to the branch responsible for providing emergency medical care services to the respective settlements.

The final layer required for the analytical procedures contains data on the settlements. Due to the characteristics of the analytical tools employed, settlements were represented as point features located at their central parts. To assess population coverage across the province, population data obtained from the National Register of Settlements were joined to the settlement layer.

The most important component of the database for the purposes of the analysis is the road network data. Constructing a topologically correct transportation network that accurately represents real-world travel patterns is a complex task associated with a considerable risk of introducing errors. This is particularly true for studies with such a large spatial extent as the present one. For this reason, a dedicated transportation network dataset was not created. Instead, the online road network data available through the network analysis tools provided by the ArcGIS Pro software package were used.

In addition to the datasets described above, the study also utilized road network data for the national and municipal road systems provided by the Road Infrastructure Agency, as well as population data from the 2021 National Population Census (1 × 1 km grid data) obtained from the National Statistical Institute for some of the visualizations.

2.3. Methods

To investigate transport accessibility to emergency medical care services, a combination of GIS-based network analysis methods was employed. Building on our previous experience in transport accessibility research, a Service Area analysis was first conducted to enable a direct comparison with previously obtained results. This analytical approach produces highly reliable results in urban environments and in areas characterized by dense transportation networks; however, this is not the case within the service area of the Center for Emergency Medical Care in Smolyan (CEMC Smolyan). To ensure comparability of the results, the analysis was performed using the same parameter settings as those adopted in our previous study of this territory (Todorov 2026).

To represent emergency medical service operations as realistically as possible, travel was modelled from the locations of the EMCBs to the territories they serve. The modelling was carried out without specifying a particular day of the week or time of day. In practice, emergency ambulances do not operate under the same traffic conditions as ordinary road users. For example, in situations where conventional vehicles would experience substantial delays due to traffic congestion, ambulances operating under emergency response conditions are able to proceed with considerably less delay by using emergency driving privileges. Although congestion still affects their travel times, its impact is substantially smaller than for ordinary vehicles. Consequently, accurately modelling ambulance movements under peak traffic conditions is extremely challenging and would not provide meaningful additional value for the purposes of the present study. Furthermore, it should be noted that the study area is not characterized by severe traffic congestion, making the influence of traffic conditions on travel times relatively limited.

The final important component of the analytical framework concerns the classification of the travel time intervals used in the analysis. To ensure consistency with the regulatory framework governing emergency medical care in Bul-

garia, the travel time intervals were defined in accordance with the provisions of Ordinance No. 3 of the Minister of Health of 6 October 2017 approving the medical standard Emergency Medicine (Ministry of Health 2026b). This standard specifies the triage categories used within the Bulgarian emergency medical care system and the recommended ambulance response times (Chapter V, Transport of the Emergency Patient, Section 4.2.1.1.2), which can be summarized as follows:

- Red Code – Critical emergency patient: A patient presenting with life-threatening signs and symptoms. The recommended ambulance response time is within 8 minutes.
- Yellow Code – Unstable or potentially unstable emergency patient: A patient with a suspected risk of deterioration and a potential threat to life, whose condition may progress to a life-threatening emergency. The recommended ambulance response time is within 20 minutes.
- Green Code – Stable emergency patient: A patient with low urgency and a minimal risk of complications or progression to a critical condition. The recommended ambulance response time is within 120 minutes.

The travel time classification adopted in the analysis includes the first two isochrone intervals, within 8 minutes and within 20 minutes, as defined by the national emergency medical care standard. No additional isochrone was introduced between these thresholds, as this would unnecessarily increase the level of detail without providing meaningful analytical benefits. In contrast, the third travel time interval required a more detailed subdivision and was therefore divided into the following categories: within 30, 45, 60, 90, and 120 minutes.

Given the primary role of the emergency medical care system in providing services to the population, the subsequent stage of the study focused on the settlement level. The next analytical procedure involved the application of Origin–Destination (OD) Cost Matrix analysis. As in the previous analysis, travel was modelled from the EMCBs to the settlements they serve.

To evaluate the current organization of the emergency medical care system, the analysis was conducted at the branch level, with accessibility modelled from each Emergency Medical Care Branch to the settlements within its service area. The resulting travel time estimates were linked to settlement-level population data and subsequently reclassified according to the previously defined travel time categories. This made it possible to assess the current level of population coverage and to identify areas characterized by reduced accessibility to emergency medical care services.

The results obtained from the Origin–Destination (OD) Cost Matrix analysis were subsequently validated to assess their reliability. For this purpose, route simulations generated using Google Maps, one of the world's most widely used routing and navigation platforms, were employed as an independent reference for comparison.

The analysis was subsequently extended to examine whether the current distribution of the Emergency Medical Care Branches and the boundaries of their service areas represent the most appropriate configuration from the perspective of transport accessibility. For this purpose, a Closest Facility analysis was performed. The analysis included all settlements and EMCBs within the study area. As with the previous analyses, travel was modelled from the branches to the settlements.

Another key parameter of the analysis was restricting the search to a single closest branch for each settlement. This approach clearly identifies settlements that can be reached more rapidly from a neighbouring branch than from the branch currently responsible for providing emergency medical care services. As will be demonstrated in the Results section, the contiguous clusters of settlements that are more accessible from neighbouring branches closely correspond to the problem areas identified by the Origin–Destination (OD) Cost Matrix analysis.

Furthermore, the Closest Facility analysis facilitates the identification of numerous settlements for which emergency medical care provision could be readily optimized through a simple reassignment of the responsible Emergency Medical Care Branch, without requiring changes to the existing infrastructure.

In the final stage of the analysis, a relatively easy-to-implement optimization scenario was proposed for two of the areas identified as problematic. Its potential impact was evaluated by performing a second Closest Facility analysis, in which two additional locations representing proposed Outstationed Emergency Medical Teams were incorporated alongside the existing Emergency Medical Care Branches.

The resulting accessibility estimates were once again linked to the settlement-level population data. To assess the potential effectiveness of the proposed optimization scenario, a comparative analysis was carried out between the results of the Closest Facility analysis representing the current configuration of the emergency medical care system and those obtained under the optimized configuration.

3. Results

3.1. Service area

At the initial stage of the study, a Service Area analysis was performed. The primary objective of this analysis was to determine whether the application of the algorithm would yield improved results compared with those obtained in our previous study conducted for the same territory (Todorov 2026).

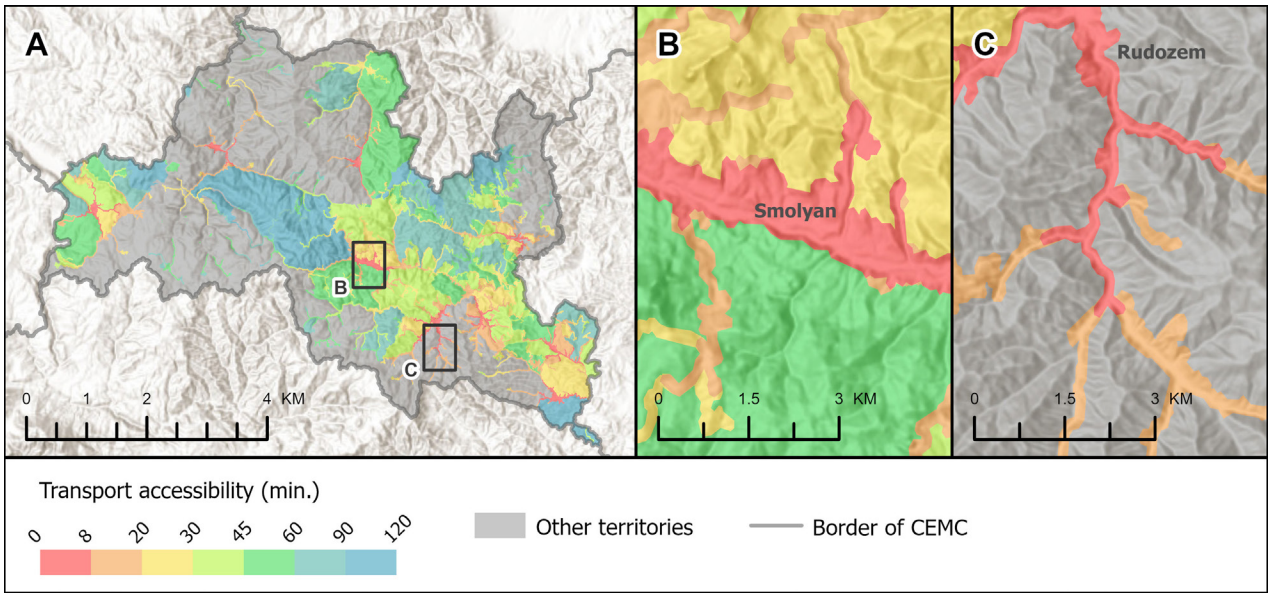

Figure 4. Service area analysis results. **A** Smolyan district **B** Smolyan **C** Rudozem.

The findings once again confirmed the conclusions of our previous study (Todorov 2026). Based on using the topological road network, the Service Area algorithm produces reliable results along the road segments themselves and within settlements where the street network is properly represented. However, areas characterized by highly dissected terrain and lower road network density remain problematic for the algorithm. As a result, extensive areas remain outside the coverage of the generated output and are visualized in grey in Fig. 4. In these territories, the analysis extent is typically limited to narrow buffers surrounding the roads and smaller settlements.

3.2. Origin–Destination Cost Matrix

To examine spatial accessibility at the settlement level, an Origin–Destination (OD) Cost Matrix analysis was conducted. Selected results are illustrated in Fig. 5.

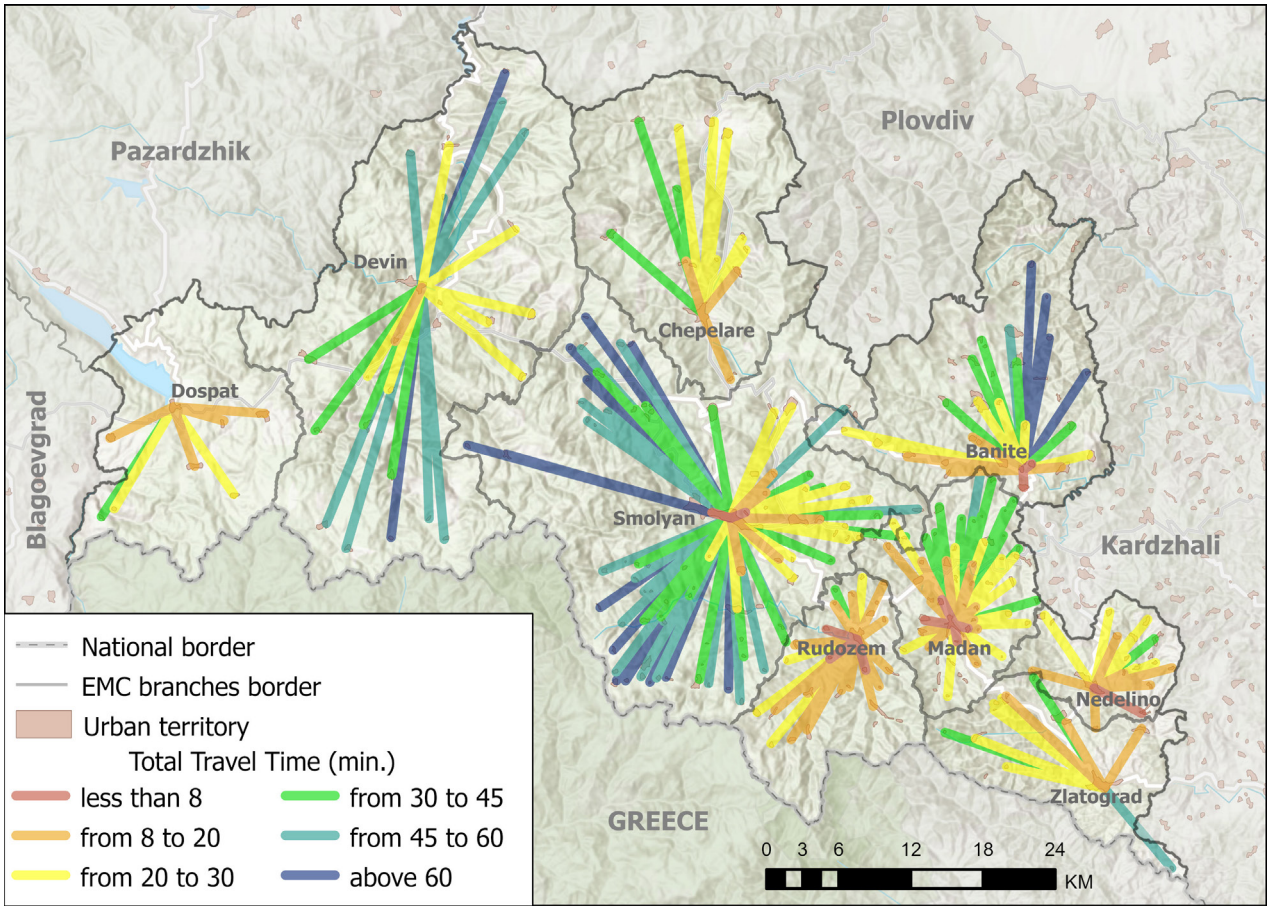

Figure 5. Origin–Destination Cost Matrix results.

The map clearly highlights the three most problematic branches: Smolyan, Devin, and Banite. The extensive area covered by the branch located in the district center, combined with the large number of settlements within its catchment area and the pronounced mountainous character of the terrain, contributes to poorer transport accessibility from the Smolyan branch to a substantial proportion of the villages it serves.

According to the results of the OD Cost Matrix analysis, only the provincial center and the village of Dunevo fall within the 8-minute travel time threshold from the location of the Smolyan branch. This result is also confirmed by the Service Area analysis, according to which most of the territory of the district center falls within the 8-minute isochrone. The easternmost neighborhoods of Ustovo, Gorno Vlahovo, and Petrovitsa are an exception, as they fall within the 8–20-minute interval. The village of Dunevo is also included within the 8-minute coverage area of the branch.

According to the 2025 statistical data, the two settlements have a combined population of slightly more than 24,000 inhabitants. The second travel time interval, from 8 to 20 minutes, includes five additional settlements with a total population of approximately 450 inhabitants. The third isochrone, from 20 to 30 minutes, adds another 16 villages to the branch's coverage area, with a population of 3,518 inhabitants. The next interval, between 30 and 45 minutes, covers a further 21 villages with a total population of 1,226 inhabitants. The 45–60-minute interval includes 24 settlements with a population of 759 inhabitants. Most of these are in the areas south of the village of Smilyan, as well as in the northwestern parts of Smolyan Municipality that are remote from the town of Smolyan. The final isochrone, exceeding 60 minutes, includes 15 settlements, six of which had no recorded population in 2025. The population of the remaining nine villages within this isochrone amounts to 178 inhabitants.

Within the territory served by the Devin Emergency Medical Care Branch, settlements with lower levels of transport accessibility are concentrated mainly in its southern part. As noted earlier, this branch serves the territories of two municipalities, Devin and Borino, encompassing a total of 23 settlements, two of which are depopulated and officially closed.

The only settlement that can be reached within the most favourable travel time interval of up to 8 minutes is the town of Devin. Consequently, slightly more than 5180 inhabitants fall within this time threshold. The 8–20-minute isochrone also includes only one settlement, the village of Grohotno, with a population of 708 inhabitants. Four additional villages, with a combined population of approximately 710 inhabitants, are located near the boundary between the two travel time intervals, requiring between 20 and 21 minutes to be reached from the branch. This suggests that under conditions of lower traffic congestion, they could also be reached in less than 20 minutes. This finding was confirmed through additional validation of the results.

In addition to these settlements, three more villages fall within the 20–30-minute interval. Their total population amounted to 1,836 inhabitants in 2025. All settlements that can be reached within 30 minutes are located within the boundaries of Devin Municipality. Four settlements, with a combined population of 2,461 inhabitants, can be reached by emergency medical teams within 30–45 minutes. Travel times between 45 and 60 minutes are required to reach eight villages with a total population of 812 inhabitants. These settlements are evenly distributed between the northern and southern peripheries of the territory served by the Devin branch. Travel times exceeding 60 minutes are recorded for two villages with a combined population of 186 inhabitants.

As illustrated in Fig. 5, settlements with travel times exceeding 30 minutes are concentrated in the northern periphery of the branch's service area, within Borino Municipality, and in the southernmost parts of Devin Municipality. While

no feasible and easily implementable alternative exists for the northern settlements, such an alternative does exist for those located in the southern part of the territory, namely the establishment of an Outstationed Emergency Medical Team (OEMT) in the village of Borino. This option was further investigated through the application of Closest Facility analysis.

The final service area in which settlements requiring more than 60 minutes to be reached from their assigned Emergency Medical Care Branch were identified is that of the Banite branch. Within this service area, four settlements fall outside the one-hour threshold. All of them are located in the northern and northeastern peripheral parts of the branch's service area. The combined population of these settlements is 21 inhabitants.

Overall, ten settlements with a total population of 592 inhabitants are characterized by travel times exceeding 30 minutes within the Banite branch service area. Given the very small population of the settlements with reduced accessibility and the absence of a feasible and economically justified alternative, no additional optimization scenarios were considered for this part of the study area.

Table 1. OD cost matrix results—settlements and population.

Izochrone (min.)		less than 8	from 8 to 20	from 20 to 30	from 30 to 45	from 45 to 60	above 60	All
Banite	Settlements	3	5	6	5	1	4	24
	Population	1,193	633	996	358	213	21	3,414
Devin	Settlements	1	1	7	4	8	2	23
	Population	5,183	708	1,836	2,461	812	186	11,186
Dospat	Settlements	1	4	2	1	0	0	8
	Population	1,838	3,598	667	681	0	0	6,784
Zlatograd	Settlements	1	3	6	2	0	0	12
	Population	5,481	2,747	821	22	0	0	9,071
Madan	Settlements	5	14	12	13	1	0	45
	Population	5,277	2,628	1,552	560	7	0	10,024
Nedelino	Settlements	2	6	7	1	0	0	16
	Population	3,134	484	729	148	0	0	4,495
Rudozem	Settlements	5	14	4	1	0	0	24
	Population	4,112	3,920	91	0	0	0	8,123
Smolyan	Settlements	2	5	16	21	24	15	83
	Population	24,131	454	3,518	1,226	759	178	30,266
Chepelare	Settlements	1	3	6	3	0	0	13
	Population	4,032	204	837	394	0	0	5,467
Smolyan district	Settlements	21	55	66	51	34	21	248
	Population	54,381	15,376	11,047	5,850	1,791	385	88,830

When the overall situation across Smolyan Province is considered, the accessibility indicators appear considerably more favourable than the branch-level analyses might suggest (Table 1). It should be noted that the analysis includes

a total of 248 urbanized areas. As of 2025, permanent population was recorded in 233 settlements. The Pamporovo resort complex was also included in the analysis, although, according to the National Statistical Institute (NSI), it has no permanent residents. The remaining 14 urbanized areas are uninhabited; nevertheless, they were retained in the analysis because they may still be used as recreational or seasonal residential areas, and their exclusion would create artificial gaps in the spatial coverage of the emergency medical care service.

Across the province, 21 settlements can be reached from their assigned Emergency Medical Care Branches within 8 minutes. These settlements have a combined population of 54,381 inhabitants, representing just under 61.22% of the province's total population. This relatively high proportion of the population covered within the shortest travel time interval is largely attributable to the high concentration of population in the municipal centers and the continuing depopulation of smaller peripheral settlements.

The second travel time interval (8–20 minutes) includes a further 55 settlements with a combined population of 15,376 inhabitants. Consequently, the first two travel time intervals together provide coverage for just under 78.53% of the province's population. The 20–30-minute isochrone encompasses an additional 66 settlements with a combined population of slightly more than 11,000 inhabitants, increasing cumulative population coverage within 30 minutes to 90.96%.

Within the 30–45-minute interval, emergency medical teams can reach a further 51 settlements with a total population of 5,850 inhabitants, while the 45–60-minute isochrone includes another 34 settlements with 1,791 inhabitants. A total of 21 settlements, with a combined population of 385 inhabitants, have travel times exceeding 60 minutes.

A spatial autocorrelation analysis using Global Moran's I was also applied to the results of the OD Cost Matrix analysis. The results clearly indicate a strongly clustered spatial pattern in the distribution of transport accessibility values. The main statistical measures obtained from the analysis were as follows:

- Moran's Index: 0.537958
- Expected Index: −0.004049
- Variance: 0.000586
- z-score: 22.381493
- p-value: ≈ 0.000000 ($p < 0.001$)

Given the very high z-score, the probability that the observed clustered spatial pattern is the result of random chance is less than 1%. From a spatial perspective, such a result is also consistent with the geographical characteristics of the study area.

In addition, a Cluster and Outlier Analysis using the Anselin Local Moran's I statistic was performed to identify the local spatial patterns underlying the global spatial autocorrelation. The results of this analysis are presented in Fig. 6.

The map clearly delineates the problematic areas characterized by High–High (HH) clusters, representing distinct spatial concentrations of settlements with high travel times from their respective emergency medical care branches and a high level of statistical significance. These clusters encompass the southernmost and northernmost parts of the service area of the Devin EMCB, the northwestern and southern parts of the Smolyan EMCB service area, and the northern part of the Banite EMCB service area.

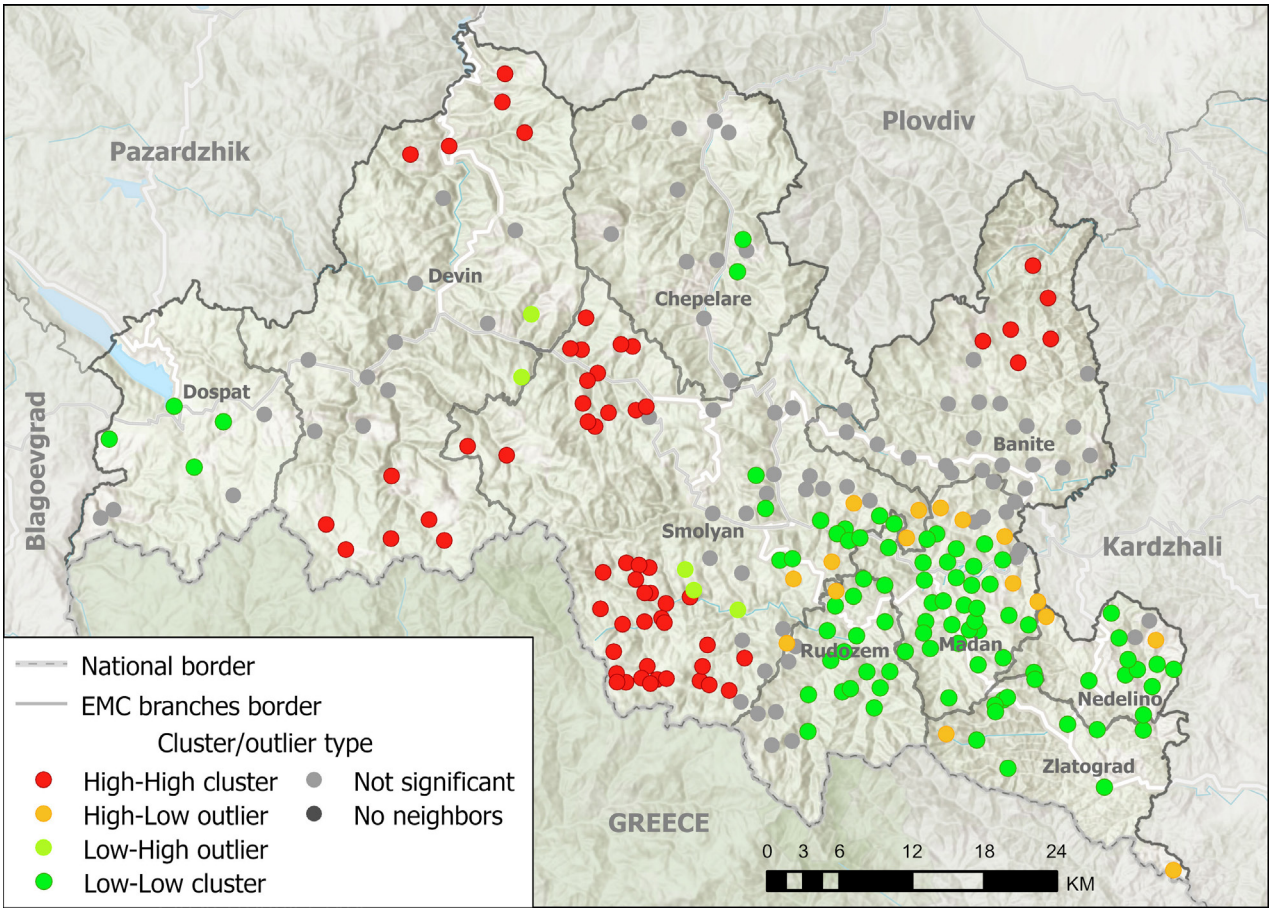

Figure 6. Cluster and Outlier Analysis.

The areas with the most favourable levels of transport accessibility are also clearly distinguishable. These correspond to Low–Low (LL) clusters, where settlements with low travel times form statistically significant spatial concentrations. Such clusters are primarily observed within the service areas of the branches covering smaller territories, particularly Rudozem and Madan, which are also characterized by a higher density of settlements, as well as Nedelino and Zlatograd.

3.3. Closest facility

The assessment of the current configuration of the emergency medical care system was further refined through the application of a Closest Facility analysis, with the objective of identifying, for each urbanized area, the Emergency Medical Care Branch that could provide the shortest travel time.

The analysis showed that 64 of the 248 settlements included in the study could be reached more quickly from a neighboring branch than from the Emergency Medical Care Branch currently responsible for serving them (Fig. 7). Their combined population amounts to 6,630 inhabitants.

Two settlements within the service area of the Devin branch could be reached more rapidly from the Dospat branch. Within the service area of the Zlatograd branch, the closest branch for two settlements is Madan, while for another two it is Nedelino. The Nedelino branch is also the closest facility for one settlement

currently assigned to the Madan branch, whereas six other settlements within the same service area could be reached more quickly from the Banite branch.

The largest number of settlements that could be reached more rapidly from neighboring branches is observed within the service area of the Smolyan branch. For a total of 51 villages currently assigned to this branch, a more favourable alternative exists among the existing emergency medical care facilities. Two neighboring branches provide the closest access for only a small number of these settlements, the Banite EMCB for one village and the Madan branch for two villages.

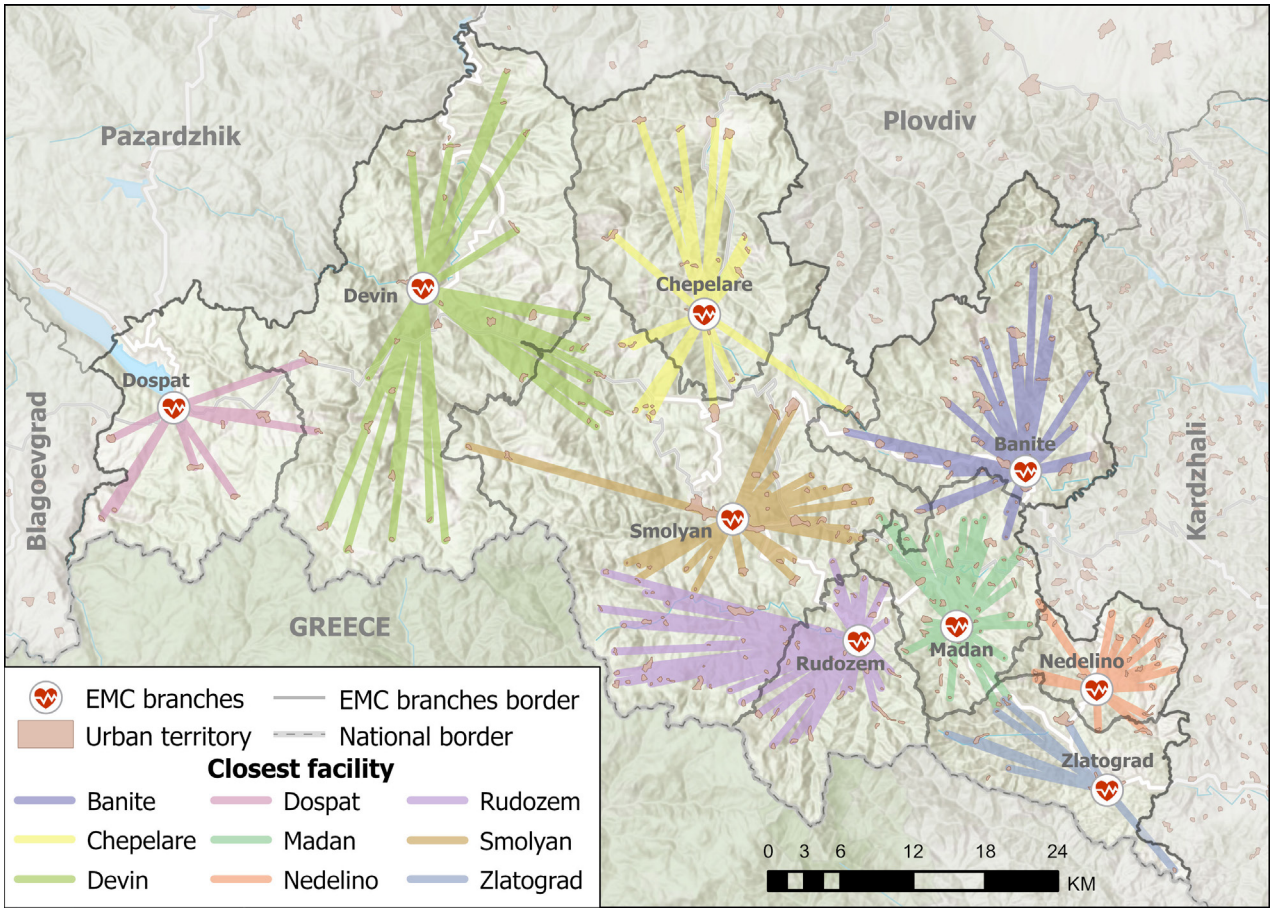

Figure 7. Closest facility results.

For a larger group of settlements (seven in total), the closest EMCB is the branch in Chepelare. All these settlements are located in the northern part of the service area of the Smolyan branch. Among them is the Pamporovo resort complex, which represents a more specific case. Here, the results depend largely on the location of the destination point used for accessibility calculations. Pamporovo extends over a considerable distance along the main road passing through the resort, and it is within the resort that the point equidistant from the Chepelare and Smolyan branches is located along the Chepelare–Smolyan road. Consequently, depending on the placement of the destination point, the closest EMCB may be either the Smolyan or the Chepelare branch.

For this reason, the two branches should be regarded as jointly responsible for providing emergency medical care services within the resort complex.

Emergency calls should therefore be dispatched to either branch according to the exact location of the incident, the urgency of the case, and the operational availability of the emergency medical teams.

The considerations outlined above are particularly important in the context of the situation that arose in early May as a result of the landslide along the third-class road III-8641 between Pamporovo and Smolyan. Additional route calculations were performed between the Smolyan EMCB and the Pamporovo resort. Under the initial conditions, when no alternative route was available around the affected road section, the travel time from the branch in the regional center to Pamporovo increased by approximately 15–20 minutes compared with normal conditions. This further highlights the importance of the Chepelare EMCB as an alternative provider of emergency medical care for incidents occurring within the Pamporovo resort.

Several of the settlements for which the Chepelare branch provides the shortest travel time coincide with the problem areas identified by the OD Cost Matrix analysis, namely the settlements located in the northwestern part of the Smolyan branch service area. The remaining settlements in this part of the service area (nine villages) can be reached most rapidly from the Devin branch.

The largest number of settlements within the service area of the Smolyan EMCB can be reached more rapidly from the Rudozem branch. A total of 32 settlements fall into this category, almost all of which are located south of the village of Smilyan in the southern part of Smolyan Municipality. These settlements were selected for further analysis, as they represent an area for which a relatively simple and cost-effective optimization scenario could be implemented.

In fact, two potential optimization scenarios were examined in greater detail. The first concerns the southern part of Smolyan Municipality. This scenario evaluates the potential impact of establishing an Outstationed Emergency Medical Team (OEMT) affiliated with the Smolyan Emergency Medical Care Branch and stationed in the village of Smilyan. The village has an existing primary healthcare facility, where it can reasonably be assumed that the space required for such a team could be provided with relatively limited investment and at comparatively low cost.

The second scenario examines the establishment of an Outstationed Emergency Medical Team affiliated with the Devin Emergency Medical Care Branch and based at the primary healthcare facility in the village of Borino. Here again, it can reasonably be assumed that the implementation of such a measure would be technically feasible and would require relatively modest financial and organizational resources.

The Closest Facility analysis was subsequently repeated after incorporating the two proposed locations for Outstationed Emergency Medical Teams in the villages of Borino and Smilyan. The results are presented in Fig. 8.

The establishment of an outstationed emergency medical team at the primary healthcare facility in Borino would make this facility the closest emergency medical care provider for all settlements located in the southern part of the service area of the Devin EMCB. These settlements were previously identified by the Origin–Destination Cost Matrix analysis as among the most problematic in terms of transport accessibility. The proposed OEMT would serve 11 settlements with a combined population of 3,545 inhabitants.

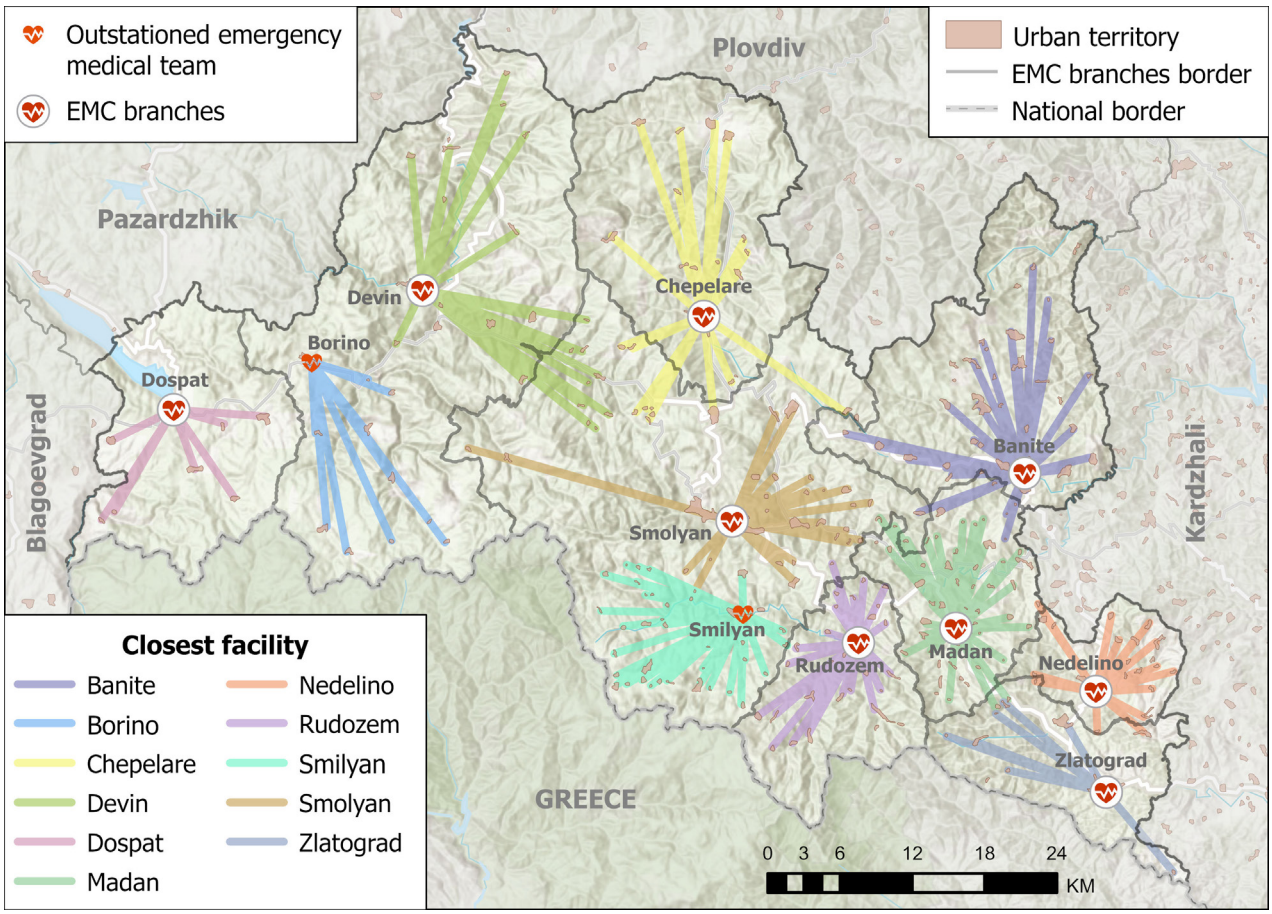

Figure 8. Closest facility results—OEMT Borino and OEMT Smilyan.

For nine of these settlements, the establishment of an outstationed team in Borino would reduce the average travel time by 10.42 minutes and the travel distance by 7.28 km. An even greater improvement would be achieved for the village of Chala, where travel time would be reduced by 27.79 minutes and travel distance by 20.16 km.

The greatest benefit, however, would be observed for the village of Borino itself. Under the proposed scenario, the entire settlement would fall within the most favourable travel time interval of up to 8 minutes. Consequently, the travel time from the responsible emergency medical care facility would decrease from approximately 30 minutes to less than 8 minutes. In fact, almost the entire settlement would be covered by the 5-minute isochrone (Fig. 9). Given that Borino has a population of 1,638 inhabitants, this represents a substantial improvement in accessibility to emergency medical care services.

The establishment of an Outstationed Emergency Medical Team in the village of Smilyan would have an even greater impact in terms of reducing travel times from the responsible emergency medical care facility. If implemented, this optimization scenario would improve transport accessibility to emergency medical care services for 36 settlements with a combined population of 2,514 inhabitants.

For most of these settlements (27 in total), travel time would be reduced by an average of 26.66 minutes, while travel distance would decrease by 17.41 km. For an additional four settlements, travel times would be reduced by 20–25

minutes, with travel distances decreasing by as much as 15.7 km for two of them. A further four settlements would experience reductions in travel time of 14–15 minutes. The smallest improvement would be observed for the village of Chokmanovo, where travel distance would decrease by 4.8 km and travel time by just under 8 minutes.

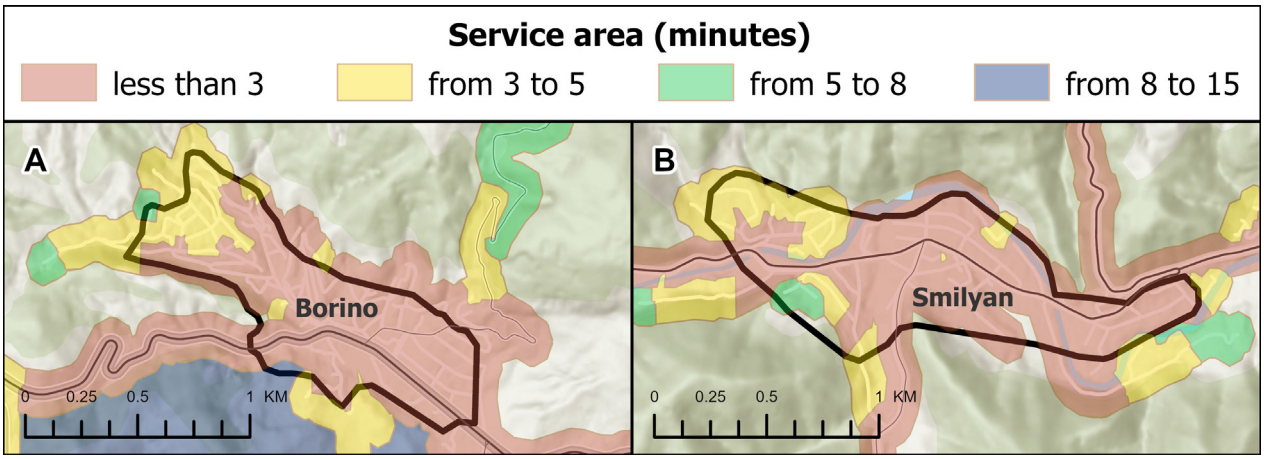

Figure 9. Service area of OEMT. **A** Borino **B** Smilyan.

The proposed OEMT would have the greatest impact on the village of Smilyan itself, which has a population of 1,559 inhabitants. For most residents, emergency medical care would become accessible within 3 minutes of travel time. Almost the entire urbanized area of the village would fall within the first two travel time intervals (up to 5 minutes), with only a few small peripheral areas remaining within the third isochrone (5–8 minutes).

It should be acknowledged that, for certain settlements, identifying a more effective organizational alternative is particularly challenging. This is the case, for example, for the villages of Mugla (98 inhabitants) and Chamla (0 inhabitants), which are in the westernmost part of the service area of the Smolyan EMCB. Owing to their geographical isolation from both the town of Smolyan and the surrounding settlements, these villages remain 50–60 minutes away from the responsible emergency medical care facility even under the simulated optimization scenarios.

A closer examination of the accessibility maps reveals several other examples of settlements facing similar constraints. These cases illustrate that, in areas characterized by highly fragmented mountainous terrain and limited transport connectivity, organizational optimization alone cannot fully overcome the geographical barriers affecting accessibility to emergency medical care services.

4. Discussion

The spatial analyses conducted in this study clearly demonstrate the need to update the National Health Map and to restructure the emergency medical care system. Similar to the study by Nikolova and Patarchanova (2024), the present study raises the same key questions: whether equal access to medical care and healthcare services, as enshrined in the Constitution of Bulgaria (NARB

2026), is genuinely ensured, and whether the current structures of the emergency medical care system correspond to existing needs and are capable of providing the required rapid response in emergency situations.

The study clearly identifies several deficiencies and shortcomings that should be carefully considered. By assessing only transport accessibility, defined as travel time from emergency medical care branches to settlements, this study does not claim to provide a comprehensive evaluation of the system as a whole. Nevertheless, it provides a solid basis for initiating a more in-depth assessment of the emergency medical care system, including a full evaluation of needs, available resources, and opportunities for their more effective spatial allocation.

Such an assessment should aim to achieve a balance between population needs and the capacity to meet them adequately, while also considering the economic efficiency of the system. It should also be recognized that some settlements objectively remain isolated from the branches responsible for serving them because of their geographical location and the specific characteristics of the terrain and road network. Given their very small population size, the implementation of measures aimed at achieving higher levels of transport accessibility may not be economically justified.

Nevertheless, the study shows that optimization is possible for a substantial proportion of settlements even within the existing network of emergency medical care branches, simply by redefining their service areas.

It is important to emphasize that this is not the only peripheral region where transport connectivity and, consequently, transport accessibility exhibit unfavourable characteristics. Similar challenges have been identified in numerous studies examining both individual regions and the territory of Bulgaria as a whole, as well as in other European countries (Patarchanov 2009; Amlaev et al. 2022; Borisova 2022; Nikolova and Patarchanova 2024; Todorov 2026).

From a methodological perspective, several characteristics of the analytical tools employed in this study should be highlighted. As discussed previously, Service Area analysis performs exceptionally well within urbanized areas and in regions characterized by a dense road network. When combined with sufficiently detailed population data and information on the spatial distribution of the population, the method enables a detailed and reliable assessment of population coverage within the individual transport accessibility isochrones.

The reliability of the results produced by this analytical approach has been repeatedly confirmed by our previous research (Todorov 2026) through validation against route simulations generated using Google Maps. Nevertheless, the limitations of the method should also be acknowledged. In mountainous regions, the analytical performance of the Service Area algorithm decreases substantially beyond the narrow corridors surrounding the road network, where the generated accessibility surfaces no longer adequately represent actual travel conditions. However, because these areas are generally uninhabited, the method can still be considered sufficiently reliable for assessing population coverage within the defined travel time intervals.

As noted previously, Origin–Destination Cost Matrix analysis was employed to evaluate the current configuration of the emergency medical care system. One methodological limitation of this approach is that accessibility is represented by a single reference point within each settlement. For the purposes of

the present study, however, this level of generalization is entirely appropriate, since the analyzed settlements occupy relatively small geographic areas. Furthermore, because the Emergency Medical Care Branches are located in the larger urban centers, these settlements are entirely covered by the 8-minute isochrone.

The results of the OD Cost Matrix analysis were further validated by calculating routes from the responsible EMCBs to all 248 urbanized areas included in the study using Google Maps. The choice of this platform for validation was deliberate, as its routing engine is based on extensive traffic and navigation data collected from millions of users over a prolonged period, providing a high level of reliability for travel time estimation.

Across all 248 urbanized areas, the mean difference between the travel times calculated by ArcGIS and Google Maps was 2 minutes and 55 seconds. Of these, 96 settlements exhibited a difference of less than 1 minute. Twelve settlements showed differences exceeding 10 minutes, while 28 settlements differed by 5–10 minutes.

It should be acknowledged, however, that it is difficult to determine whether these discrepancies arise from the routing algorithm or from the underlying road network data used by either ArcGIS or Google Maps. Both platforms contain certain omissions and inaccuracies in their road network datasets, particularly in remote mountainous areas and on roads providing access to very small or depopulated settlements. Similar observations have also been reported by Popescu and Bărbulescu (2025).

A representative example is the village of Chamla. The route generated by Google Maps follows the municipal road SML2240 to approximately 2 km beyond the village of Mugla, after which it assumes a pedestrian route across the mountain. When settlements exhibiting such obvious inconsistencies between the routes generated by the two platforms are excluded from the analysis, together with the settlements hosting the Emergency Medical Care Branches (for which no differences were recorded), the mean discrepancy decreases to 2 minutes and 14 seconds.

Considering that the present study evaluates only transport accessibility and does not incorporate additional operational factors, such as ambulance dispatch and response times, which would inevitably increase the total response time, the performance of the routing algorithm can be regarded as sufficiently reliable for the purposes of the analysis.

Since the Closest Facility analysis relies on the same road network data and routing algorithm to determine the nearest Emergency Medical Care Branch for each settlement, the results of the validation may reasonably be considered applicable to this analytical approach as well.

5. Conclusion

The present study raises several important issues. First and foremost, the findings highlight the need for reforms in the organizational structure of the emergency medical care system. As demonstrated by the results, some of the identified shortcomings could be addressed without the need for complex or costly interventions, simply by redefining the service areas of the existing Emergency Medical Care Branches. For other problem areas, the study proposes relatively

low-cost optimization measures capable of substantially reducing travel times from the branches to the affected settlements.

It should be emphasized, however, that the present study focuses primarily on transport accessibility to emergency medical care services. Consequently, a more comprehensive assessment of the available resources and operational capacity of individual Emergency Medical Care Branches is required before the most appropriate solutions for local communities can be identified and implemented.

In this regard, the methodological framework could also be further extended through the application of accessibility measures such as the Two-Step Floating Catchment Area (2SFCA) method (Luo and Wang 2003; Luo and Qi 2009; Delamater 2013; McGrail and Humphreys 2014; Kiani et al. 2021) or one of its modified variants, such as the Enhanced Two-Step Floating Catchment Area (E2SFCA) method (Luo and Qi 2009; Kiani et al. 2021; Jörg and Haldimann 2023). These approaches would make it possible to evaluate not only transport accessibility but also the balance between the demand for emergency medical care services and the available service capacity.

Achieving this objective will require close collaboration with the Ministry of Health and the Centers for Emergency Medical Care in order to overcome existing limitations related to the availability of the data required to support more advanced spatial analyses.

It is also important to emphasize that the proposed optimization measures are closely linked to the need to update the National Health Map, which is currently outdated and no longer adequately reflects the healthcare needs of the population. In this context, it should be stressed that, in order to function as an effective planning instrument, the National Health Map should evolve from a static document consisting primarily of textual descriptions and tabular data representing the situation at a particular point in time into a dynamic, operational system for the collection, storage, analysis, and visualization of spatial data on healthcare resources, population needs, and other relevant indicators. Such a transformation would provide a substantially stronger evidence base for decision-making and would support more effective planning and management of the healthcare system.

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Additional information

Conflict of interest

No conflict of interest was declared.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.
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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.