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Research Article

Forest road network planning based on topological measures in Hyrcanian recreational forest parks using graph theory

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Abstract

Road network connectivity significantly influences the total cost of transportation in recreation services. With recent advancements in mathematical sciences and computer technology, structural analysis using graph theory has become practical. The application of graph theory offers several benefits, including the evaluation of connectivity levels, network transportation speed, accessibility, identification of critical junctions, and detection of traffic-reducing cycles that enhance safe and convenient travel for tourists. In this paper, the existing road networks of eight recreational forest parks (Mirza Kouchak Khan, Zare, Talar, Endargeli, Javarem, Izadshahr, Haloomsar and Abbasabad) in Mazandaran Province were analyzed using graph theory. Moreover, new roads were proposed to enhance network connectivity for recreational services. Root nodes, articulation nodes, links and sub-graphs were considered as graph components, while network density, road spacing, alpha index (α), beta index (β), P index (π), eta index (η), number of cycles (u), gamma index (γ) and detour index (DI) were considered as topological and geometric measures. New road segments were proposed based on topologic standards to improve the efficiency of road networks with weak connectivity. The proposed approach was applied to eight test networks in the central highland of the Hyrcanian forests, northern Iran. The results showed that the means of the articulation nodes, total nodes, links, sub-graphs, α, β, π, η, u and γ in the forest land use with recreation services were 0.5, 7.25, 7.25, 1.12, 0.07, 0.95, 2.00, 1.13, 1.12 and 0.46, respectively. As a result of supplementary roads, road density increased by 15.60%, 20.30%, 37.20%, 34.3%, 8.60% in Endargeli, Javarem, Izadshahr, Haloomsar and Abbasabad, respectively. Additionally, the α index improved from 0 to 0.12, 0.2, 0.17, 0.14 and 0.33 in these study locations. Structural properties of road networks with weak connectivity were improved to the standard range by the addition of supplementary roads. The findings of the present study showed that completing the networks by introducing cycles can enhance other graph theory indicators and improve overall connectivity.

Keywords: Graph theory, Connectivity, Road network, Recreational service.

1. Introduction

Forest road network connectivity significantly influences the total cost of transportation in recreational services (Mostafa et al., 2015; Ascensão et al., 2019; Kazama et al., 2021). Accessibility is a key indicator for understanding the spatial pattern of road networks, as it facilitates efficient control and service delivery within forests (Ballou et al., 2002; Tacnet et al., 2012; Mostafa et al., 2017). The most fundamental measure of accessibility involves network connectivity, where a network is represented as a connectivity matrix linking each node to its adjacent nodes (Levinson & Yerra, 2006; Ghaffarian & Sobhani, 2007; Parsakhoo & Lotfalian, 2017). Graph measures provide a powerful tool for describing accessibility of the network based

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on geometric structures (Yildirim & Kadi, 2020; Gharaee et al., 2021). Graph theory, a branch of mathematics, focuses on how networks can be represented and analyzed to measure their properties (Thompson et al., 2007; Çalışkan & Sevim, 2021). A graph consists of a set of nodes and a set of road links between two nodes. Road network can be embodied as a set of nodes representing spatial locations and a set of links representing connections possess many different structural properties, displaying both topological and geometric variations (Xie & Levinson, 2007; Yang et al., 2009).

In the design of forest road networks for tourism purposes, network connectivity and ease of access are more important than any other technical indicator. Therefore, methods such as Buckmund, commonly used for evaluating forest road networks for timber harvesting and transportation purposes, are not suitable for evaluating recreational road systems. Graph theory offers several advantages for evaluating such networks, including evaluating the level of connectivity, network transportation speed, accessibility, identifying junctions, and the presence of traffic-reducing cycles, all of which contribute to safe and convenient tourist transportation. In recent years, research on transportation networks has shifted from simple topological measures to more complex measures of graph theory (Xie & Levinson, 2007; Eker et al., 2013; Heinimann, 2017). Analysis of forest road networks using graph theory indices can improve connectivity while reducing traffic pressure (Anderson & Nelson, 2004; Mostafa et al., 2015). Graph-based analysis is cost-effective, more accurate and scalable beyond small case studies. Liu & Dong (2008) detected the most appropriate road networks using a circuitry index, *b* line-node ratio, and *g* connectivity index in graph theory. Similarly, Watanabe (2010) reported that proximity analysis of graph links could be efficiently conducted using digital maps. As the construction of new forest roads requires significant investments, graph theory provides a practical tool to identify and priorities road segments where alternative connections would yield the greatest benefits (Sohouenou et al., 2020).

Zhao et al. (2024) proposed a graph-based road extraction algorithm for high-resolution remote sensing images, known as DSVNet. By introducing deformable attention, the model significantly improves both computational efficiency and road network detection performance. Graph-based algorithm is capable of iteratively identifying and removing network elements that do not contribute to transportation functionality, such as self-loops, dead-ends, and interstitial nodes located along the same road segment (Pung et al., 2022). Previous studies on connectivity pattern of road networks have primarily focused on simplified patterns or relied on manual analysis. In contrast, the current study proposes a series of measures based on graph theory to evaluate and enhance the geometric structure and connectivity of road networks based on considering multiple services of wood transportation and recreational services. The proposed approach was applied to 20 test networks in the central highland of the Hyrcanian forests in northern Iran. The main objectives of this research were: (1) to measure the graph components and technical properties of roads with recreational services, (2) to compare the graph components of studied roads with standards of graph theory, and (3) to design supplementary roads in areas exhibiting weak connectivity.

2. Materials and methods

2.1. Study area

Iran's Hyrcanian forests are classified as temperate deciduous forests, with small patches of Mediterranean-type woody vegetation. In recent years, recreational use of these forests has gained increased attention, both due to increasing environmental concerns and generating revenues, sometimes much more than commercial timber forest production (Contreras & Chung, 2007). This study was carried out on road networks consisting of eight forest parks (Mirza, Kouchak Khan, Zare, Talar, Endargeli, Javarem, Izadshahr, Haloomsar and Abbasabad) in Mazandaran province, northern Iran, (Figure 1). A unique feature of the study areas is that these forest parks host tourists throughout the year, especially during holidays. Also, during peak traffic days and hours, the problem of network congestion and traffic delays become clearly evident. The characteristics of the study areas are summarized in Table 1. The forest road networks in these forest parks are primarily designed to support recreational services, including forest walking, camping, ecotherapy, and sports.

2.2 Measurements

In this study, eight heavily trafficked forest parks in Mazandaran Province were first identified. Road network maps were obtained from relevant organizations, and their digital information was entered into Arc GIS.

Subsequently, graph components, including root, articulation node, links, and sub-graphs, were determined and marked for each road network (Figure 2). In the next step, the structural and connectivity properties of the road networks were calculated regarding recreational functions. These properties are defined as follows:

Road network density ($R_{density}$): represents the coverage of linear meters of road per hectare as expressed in Equation (1).

$$R_{density} = \frac{R_{Length}}{A} \qquad (1)$$

where A is coverage of area in ha and R_{Length} represents millage of road in m.

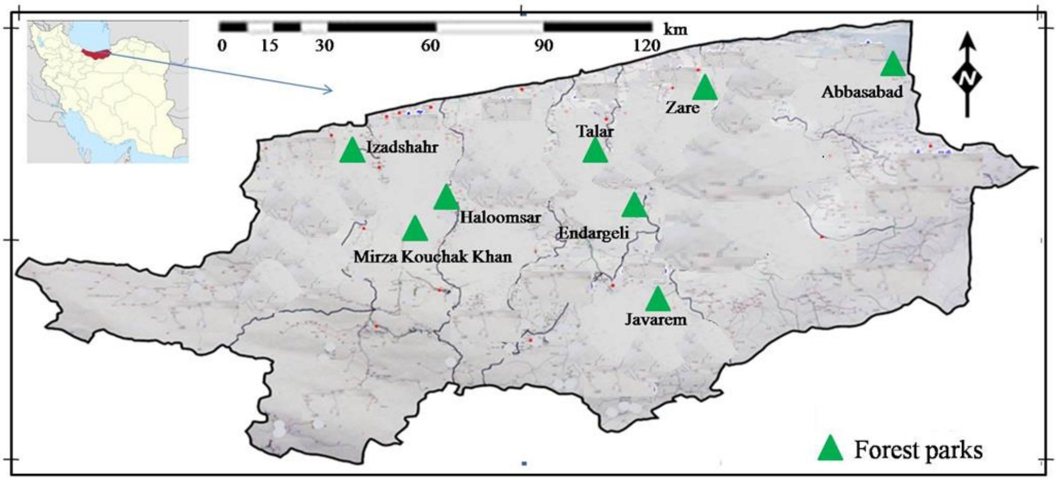

Figure 1. General location of the eight study forest parks in Mazandaran Province, northern Iran

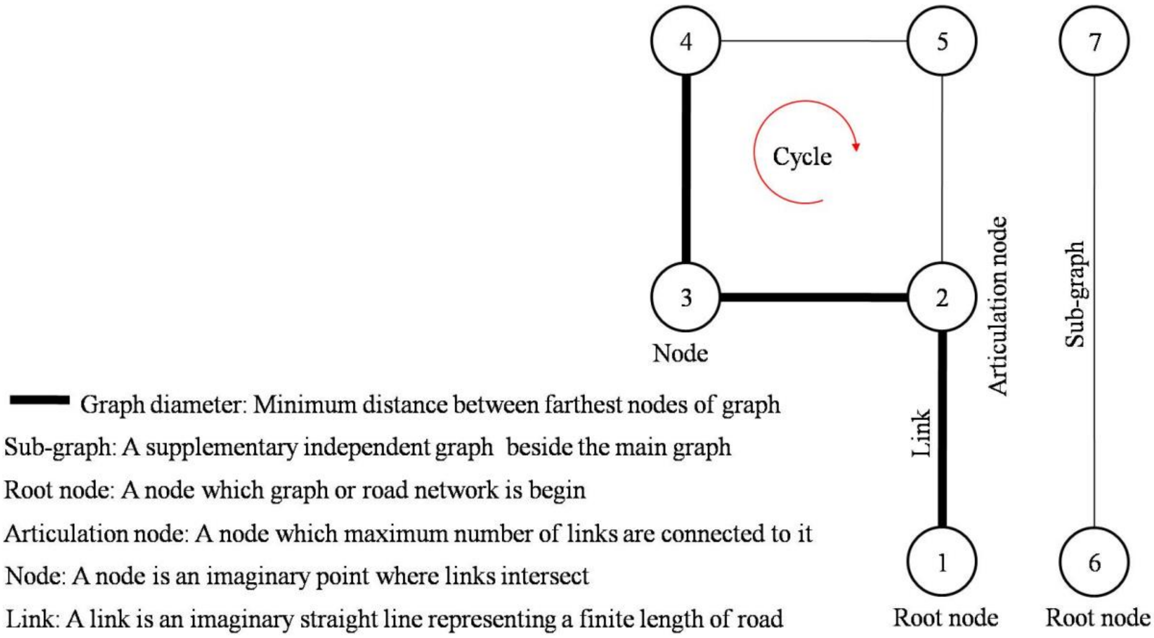

Figure 2. Illustration of graph components, including root nodes, articulation nodes, links, and sub-graphs

Road spacing (Rs): refers to the average distances between roads, as defined in Equation (2). A lower value of road spacing indicates greater network coverage (Mostafa et al., 2015).

$$R_s = \frac{10000}{R_{density}} \quad (2)$$

Alpha index (α): represents a measure of connectivity, which evaluates the number of cycles in a graph in comparison with the maximum possible number of cycles. A higher alpha index indicates a more connected network (Rodrigue et al., 2006). Its value ranges from 0 for a simple value to 1 for a highly complex value as shown in Equation (3).

$$\alpha = \frac{e - v + 1}{2v - 5} \quad (3)$$

where *e* is the number of links and *v* is the number of nodes.

Table 1. Key characteristics of the study areas in Mazandaran Province, northern Iran

location	Road service	Latitude	Longitude	Altitude (m)	Slope(%)	Climate	Bedrock structure	Species
MirzaKouchakKhan	Recreation	36˚17′42″	52˚22′11″	50-250	30.00	Mid moist	Marl-Limestone	Hornbeam, Ironwood
Endargeli	Recreation	36˚20′44″	52˚54′37″	50-250	25.00	Moist	Limestone	Hornbeam, Ironwood
Javarem	Recreation	36˚12′45″	52˚54′14″	200-700	35.00	Very moist	Marl-Sand-Limestone	Hornbeam, Ironwood
Zare	Recreation	36˚32′38″	53˚07′08″	20-80	20.00	Very moist	Marl-Sand-Limestone	Hornbeam, Ironwood
Izadshahr	Recreation	36 32′05″	52˚06′39″	20-100	5.00	Moist	Marl-Limestone	Hornbeam, Ironwood
Haloomsar	Recreation	36˚24′14″	52˚20′07″	20-100	5.00	Very moist	Conglomerate	Maple, Alder
Abbasabad	Recreation	36˚40′00″	53˚35′00″	50-350	11.00	Mid moist	Marl-Limestone	Hornbeam, Ironwood
Talar	Recreation	36˚23′17″	52˚49′58″	50-175	25.00	Mediterranean	Marl-Silt-Sandstone	Hornbeam, Ironwood

Beta index (β): is a basic measures of the level of connectivity in a graph and is defined as the relationship between the number of links (e) over the number of nodes (v). A simple network has an index value of less than 1, while a more complex network often has a value of greater than 1, as shown in Equation (4).

$$\beta = \frac{e}{v} \quad (4)$$

P index (π): represents the relationship between the total length (L) and the distance along its diameter (D), as shown in Equation (5). A higher P index shows a more well-developed network. The graph diameter is defined as the length of the shortest path between the most distant nodes within the graph, and it was measured using ArcGIS (Rodrigue et al., 2006).

$$\pi = \frac{L}{D} \quad (5)$$

Eta index (η): represents the average length per link. Adding new nodes will cause the eta index to decrease as the average length per link declines, as shown in Equation (6). η index is used as a measure of speed in a network.

$$\eta = \frac{L}{e} \quad (6)$$

Number of cycles (u): the maximum number of independent cycles in a graph is estimated through the number of nodes (v), links (e) and sub-graphs (p), as shown in Equation (7). For simple networks, u is 0 since they have no cycles (Mostafa et al., 2017).

$$u = e - v + p \quad (7)$$

Gamma index (ɣ): is a measure of connectivity that considers the relationship between the number of observed links and the maximum possible number of links, as shown in Equation (8). The value of gamma ranges between 0 and 1, where 1 indicates a fully connected network (Rodrigue et al., 2006).

$$\gamma = \frac{e}{3(v - 2)} \quad (8)$$

Detour index (*DI*): is a measure of the efficiency of a road network in terms of how well it overcomes distance or friction of space, as presented in Equation (9). The complexity of the topography is often a key indicator of the level of detour (Mostafa et al., 2017).

$$DI = \frac{d}{L} \quad (9)$$

where *d* is the length of road in meter and *L* is the real road length of roads in meter.

The closer the *DI* is to one, the more spatially efficient the network is. The results of the proposed approach were then compared with the standard graph for each test network. The standards of the reference graph are summarized in Table 2.

Finally, after evaluating the road network, we developed the existing roads with weak connectivity. The new routes were then delineated on the ground using a global positioning system (GPS), considering slope gradients, geological structures, and hydrological maps. For each test network, the surveyed routes were then assessed using graph theory to improve their structural and geometric characteristics. Common recreational services in the study areas include forest walks, camping, ecotherapy, and sports. In designing the complementary routes, efforts were made to ensure that they pass through areas that have the potential to offer these services.

3. Results and Discussion

3.1. Development of the existing roads with recreational objective

Table 3 shows the technical characteristics of the road network in forest land use with recreational services. Overall, the mean road density and road spacing were 38.10 m ha^{-1} and 586.0 m, respectively. The minimum road density of 4.30 m ha^{-1} was observed in Izadshahr, while the maximum value of 66.70 m ha^{-1} was found in Endargely. Transportation and recreation are inherently linked in many national parks (Hallo & Manning, 2009). This is particularly true of parks within the Hyrcanian forests, where much of the visitor use is concentrated along roads, and trails. A road network with poor standards can hamper recreational carrying capacity. Additionally, this can affect income and increase the poverty rate for people living in forest villages (Yu et al., 2020).

Table 2. Characteristics of the standard graph used for the evaluation of the forest road network (Rodrigue et al., 2006; Mostafa et al., 2015; Mostafa et al., 2017)

Index	α	β	γ	u	***DI***
Recreation	$1 \geq \alpha \geq 0.2$	$2.5 \geq \beta \geq 1$	$1 \geq \gamma \geq 0.33$	$4 \geq u \geq 2$	0.8–1

Table 3. Technical characteristics of the road networks in forests with recreational use

Park	**Area (ha)**	**Road length (km)**	**Density (m ha^{-1})**	**Road spacing (m)**
Mirza Kouchak Khan	379	6710	17.70	564.80
Endargeli	48	3200	66.70	150.00
Javarem	365	4300	11.80	848.80
Zare	61	3700	60.60	164.90
Izadshahr	3482	15000	4.30	2321.30
Haloomsar	55	2325	42.30	236.50
Abbasabad	138	8000	58.00	172.50
Talar	147	6415	43.60	229.10
Mean	584.4	6206.2	38.10	586.00

The spatial location of different nodes and links as well as graph diameters in the forest land use aimed at recreational services is illustrated in Figure 3. This structure aligns with the findings of Novikov et al. (2022). They reported that the road and path network are a network consisting of paths, parking lots and areas, all interconnected for the convenience of using all functional areas of the territory. The average values for root nodes, articulation nodes, total nodes, links and sub-graphs were 1.50, 0.50, 7.25, 7.25 and 1.12, respectively. Additionally, the mean values for graph diameter, α, β, π, η, u and γ were 3.20, 0.07, 0.95, 2.00, 1.13, 1.12 and 0.46, respectively (Table 4). These values suggest a poor carrying capacity of the road networks in some areas, as the average α value is less than 0.33 (Rodrigue et al., 2006; Mostafa et al., 2015; Mostafa et al., 2017). The β index is one and greater where networks are highly connected. Simple networks have values less than one; while a connected network involving a single circuit has a value of one. Increasing the links in the road network enhances connectivity measures (Kofi, 2010; Sarkar, 2013; Sreelekha et al., 2014; Sreelekha et al., 2016). The lack of necessary funding for road construction, as well as difficult tolls for designing and building the route, are among the most important reasons for the weakness in network communications, which aligns with the findings of Mostafa et al. (2017) findings.

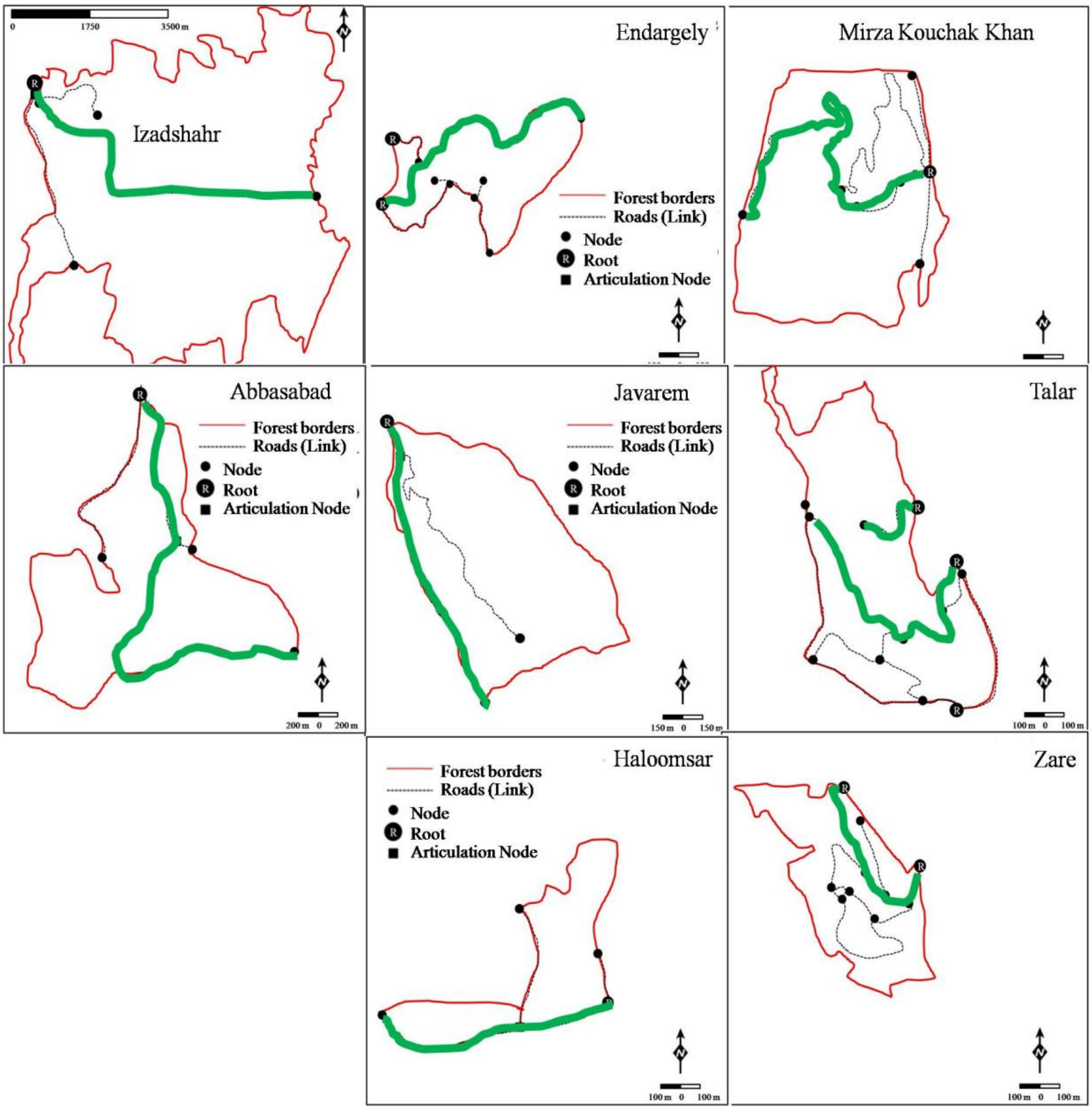

Figure 3. Graph components and diameter in forests with recreational use

As shown in Figure 4, the α, β and u indices of the road network in the sites of Endargely, Javarem, Izadshahr, Haloomsar and Abbasabad were lower compared to the standard graph. In contrast, the graph properties of the road network in Mirza Kouchak Khan, Zare and Talar were better than those in the other forests with recreational use. The lower-than-standard values of mentioned indices in the forests indicate that these areas need network development and new route design. The defect in the diameter of the network is a major issue in the Endargely, Javarem and Haloomsar road networks from the perspective of graph theory. As shown in Figure 3, all the forest roads in these areas are positioned near the forest border, which, according to Sreelekha et al. (2016) findings, can be addressed by analyzing the spatial distribution of the network and creating complementary routes.

3.2 Development of supplementary roads in forests with recreational use

Supplementary roads were designed with lengths of 0.50, 0.90, 5.50, 0.80 and 0.70 km for the sites of Endargeli, Javarem, Izadshahr, Haloomsar and Abbasabad, respectively (Figure 5).

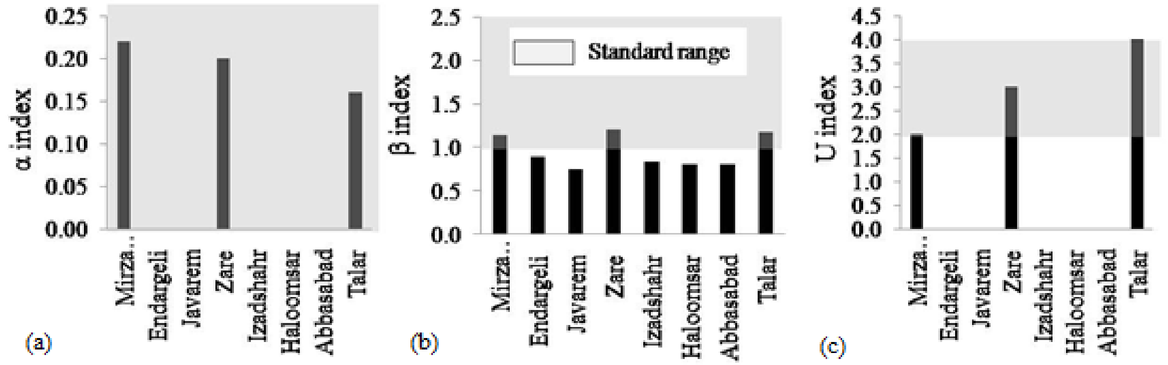

Figure4. Components of recreational road network graph compared to the standard range

Table 4. Graph characteristics of the road networks in forests with timber harvesting usage

Park	**Root node**	**Articulation node**	**Node**	**Link**	**Sub graph**	**Graph diameter (km)**	α	β	π	**η**	**u**	γ	**DI**
Mirza Kouchak Khan	1.00	0.00	7.00	8.00	1.00	4.20	0.22	1.14	1.45	0.84	2	0.53	0.91
Endargeli	2.00	0.00	9.00	8.00	1.00	2.40	0.00	0.89	1.25	0.40	0	0.38	0.94
Javarem	1.00	1.00	4.00	3.00	1.00	2.40	0.00	0.75	1.53	1.43	0	0.50	0.85
Zare	2.00	0.00	10.00	12.00	1.00	1.70	0.20	1.20	1.98	0.31	3	0.50	0.91
Izadshahr	1.00	1.00	6.00	5.00	1.00	7.20	0.00	0.83	1.93	3.00	0	0.42	0.93
Haloomsar	2.00	1.00	5.00	4.00	1.00	1.40	0.00	0.80	1.50	0.58	0	0.44	0.90
Abbasabad	1.00	1.00	5.00	4.00	1.00	5.20	0.00	0.80	1.37	2.00	0	0.44	0.89
Talar	3.00	0.00	12.00	14.00	2.00	1.20	0.16	1.17	4.98	0.46	4	0.47	0.93
Mean	1.50	0.50	7.25	7.25	1.12	3.20	0.07	0.95	2.00	1.13	1.12	0.46	0.91

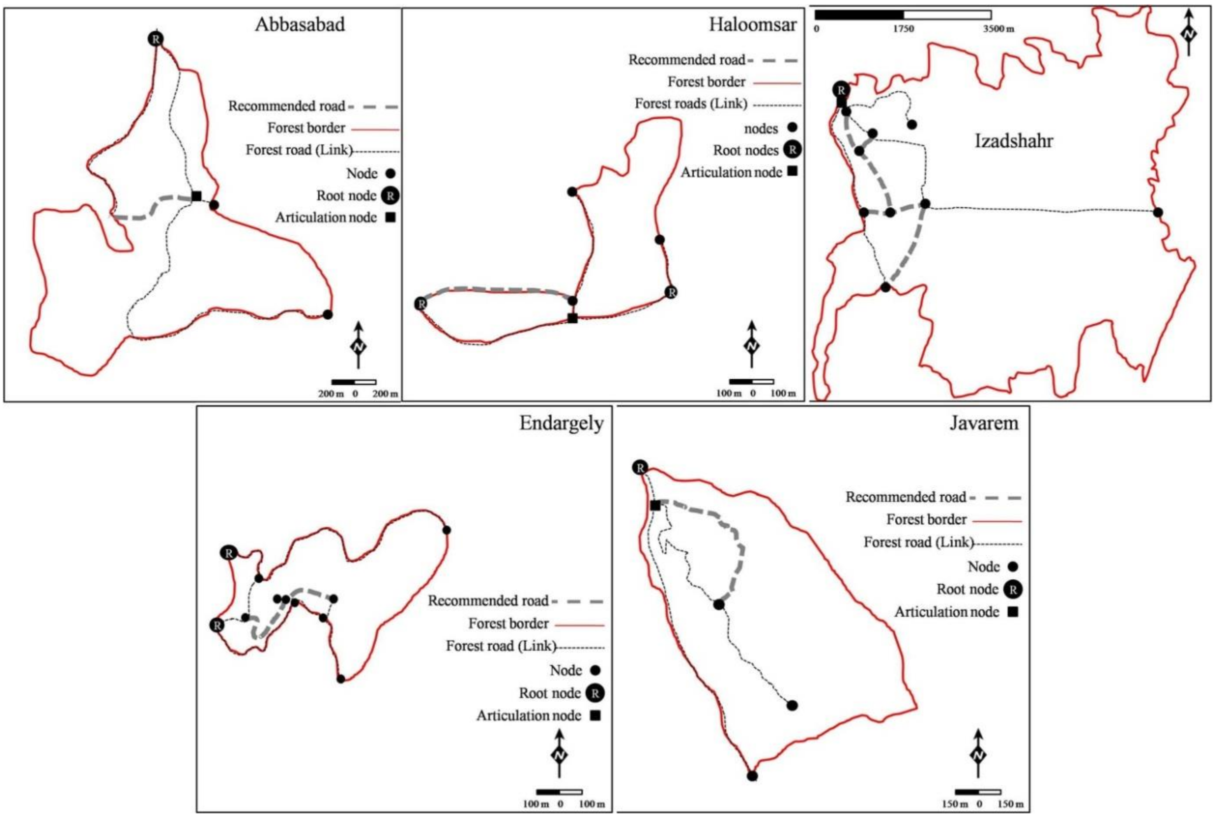

Figure 5. Supplementary roads recommended for forests with recreational use

As a result of implementing supplementary roads with focusing on creating cycles, adding connecting links, and removing redundant links, road density increased by 15.60%, 20.30%, 37.20%, 34.3%, 8.60%, respectively. The α index in Endargeli, Javarem, Izadshahr, Haloomsar and Abbasabad improved from 0 to 0.12, 0.2, 0.17, 0.14 and 0.33, respectively. Moreover, the β index was increased by 22.50%, 33.30%, 53.00%, 25.00% and 25.00% in the same locations, respectively. The γ index improved from 0 to 1 in all forest parks (Table 5). Daniel et al. (2020) studied the connectivity and coverage of road networks using graph theory. They found a negative correlation coefficient for the Eta index and a positive correlation for the alpha index and gamma indices with road network density. Similarly, Liu et al. (2024) conducted a research on the design of road in forest parks, the results of which provide valuable information about the optimal distribution of road and how to improve graph indicators. They proposed three structures of the graph including the structure focusing on the external boundaries, the pothole structure and the linear structure. According to their findings, the pothole structure is directly related to the vertices of the polygon. These act as branches of the main skeleton and connect the main pathways with peripheral boundaries. Therefore, this structure is more efficient due to having multiple cycles. These findings align with the results of current research. We found that road connectivity improved by designing cycles in the graph and increasing the U index.

Table 5. Technical characteristics of forest road networks after designing supplementary recreation roads

Graph properties	**Location**				
	Endargeli	**Javarem**	**Izadshahr**	**Haloomsar**	**Abbasabad**
Road length (km)	3.70	5.20	20.50	3.12	8.70
Density (m ha^{-1})	77.10	14.20	5.90	56.80	63.00
Road spacing (m)	129.70	704.20	1694.90	176.10	158.70
Articulation node	0.00	1.00	1.00	1.00	1.00
Node	11.00	5.00	11.00	6.00	4.00
Link	11.00	5.00	14.00	6.00	4.00
Sub-graph	1.00	1.00	1.00	1.00	1.00
α	0.06	0.020	0.23	0.14	0.33
β	1.00	1.27	2.85	2.23	1.67
π	1.54	2.17	2.85	2.23	1.67
η	0.34	1.04	1.46	0.52	2.17
U	2.00	1.00	4.00	1.00	1.00
γ	0.41	0.55	0.52	0.50	0.67

4. Conclusions

Previous research on forest road assessment has paid less attention to the issue of network connectivity for better tourism, as national forestry practices were based on timber exploitation. However, today, given the importance of recreational services and the multiple functions of forest road networks, more opportunity has been provided to examine the structural nature of the road graph. The present study, by finding network communication challenges and providing graph modification solutions by designing more links and cycles and removing excess links, was able to create a new approach to evaluating forest roads for tourism applications. Results showed that 37.5% of the recreational road networks has a complex pattern, indicating effective service connectivity. Structural characteristics of the road networks with weak service connectivity were improved by planning supplementary roads. Our findings confirm that enhanced connectivity tends to improve both accessibility and mobility within the road network. Measures of the network connectivity can be useful in research linking travel behavior for recreation development. Therefore, graph theory offers a robust approach for analyzing numerous alternative road networks and determining the most efficient one for tourism. It is recommended that existing road networks in the country's most visited forest parks be evaluated using graph theory and possible deficiencies be addressed through complementary routes. It is also suggested that in the designing of new forest parks, various communication route options should be designed and evaluated using graph indicators to select the optimal route networks.

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توسعه شبکه جاده های جنگلی بر اساس ملاحظات توپولوژیکی و با هدف گردشگری در جنگل‌های هیرکانی

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چکیده

اتصال شبکه جاده ای بر هزینه کل حمل و نقل در خدمات تفریحی تأثیر می گذارد. در روش‌های ارزیابی سنتی، سیستم‌های ارزیابی نمی‌توانند با نیاز دسترسی پایدار و کارآمد به جنگل سازگار شوند. بنابراین امروزه با توجه به پیشرفت در علوم ریاضی و دانش کامپیوتر، تحلیل ساختاری با استفاده از نظریه گراف در حال کاربردی شدن است. در این مقاله، ابتدا شبکه‌های جاده‌ای جنگلی موجود در استان مازندران (میرزا کوچک خان، زارع، تالار، اندرگلی، جوارم، ایزدشهر، حلومسر و عباس آباد) بر اساس مفاهیم معرفی‌شده در تئوری گراف تحلیل و سپس اتصال شبکه با توجه به خدمات گردشگری بررسی و توسعه داده شد.گره‌های ریشه، گره‌های مفصلی، پیوندها و زیرشبکه به عنوان اجزایگراف در نظر گرفته شدند، در حالی که تراکم شبکه، فاصله راه، شاخص آلفا(α)، شاخص بتا(β)، شاخص پی (π)، شاخصاتا (η)تعداد چرخه‌ها(u)، شاخص گاما (ɣ) و شاخص انحراف (DI) به‌عنوان معیارهای توپولوژیکی و هندسی در نظر گرفته شدند. بخش های جدید بر اساس استانداردهای توپولوژیکی برای بهبود کارایی شبکه های جاده ای با اتصال ضعیف پیشنهاد شد. رویکرد پیشنهادی برای۸ شبکه آزمایشی در ارتفاعات مرکزی جنگل‌های هیرکانی، شمال ایران اعمال شد. نتایج نشان داد که میانگین گره‌های مفصلی، کل گره‌ها، پیوندها،زیرگراف،α، β، π، η، u و ɣ در کاربری جنگلی با سرویس گردشگری به ترتیب ۰.۵، ۷.۲۵، ۷.۲۵، ۱.۱۲، ۰.۰۷، ۰.۹۵ بود. ، ۲.۰۰، ۱.۱۳، ۱.۱۲ و ۰.۴۶ بود. در نتیجه راه های تکمیلی تراکم جاده‌ها در اندرگلی،جوارم، ایزدشهر، هالومسر و عباس آباد به ترتیب به ۱۵/۶۰، ۲۰/۳۰، ۳۷/۲۰، ۳۴/۳، ۸/۶۰ افزایش یافت که منجر به بهبود شاخص α از ۰ به ۰.۱۲، ۰.۲، ۰.۱۷، ۰.۱۴ و ۰.۳۳ در مکان های ذکر شده گردید. ویژگی‌های ساختاری شبکه‌های جاده‌ای با اتصال ضعیف با طراحی جاده‌های تکمیلی به محدوده استاندارد ارتقا یافت. اندازه‌گیری ساختار شبکه راه‌ها می‌تواند برای مهندسان جنگل، برنامه‌ریزان شهری و تصمیم‌گیران برای دستیابی به اهداف مختلف مفید باشد. نتایج مطالعه حاضر نشان داد که با تکمیل شبکه از طریق پیاده سازی چرخه می توان سایر شاخص های نظریه گراف را بهبود بخشید و سطح ارتباطات را ارتقا داد.

واژه‌های کلیدی: حمل و نقل الوار، خدمات تفریحی، شبکه راه، قابلیت اتصال، نظریه گراف.

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