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Communication

Comparisons of Estimated Circuity Factor of Forest Roads with Different Vertical Heights in Mountainous Areas, Republic of Korea

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Abstract: Distance is one of the important factors in determining transportation cost and travel time, and it can be easily estimated by measuring the circuity of road networks. This study calculated the circuity factors to estimate the network distance for 27 forest roads (about 105 km) in South Korea. For this purpose, ridge, mid-slope, and valley roads were classified according to the construction location of the mountain slope, and the weighted and unweighted circuity factor (each 500-m section) were calculated. The average value of weighted circuity was 1.55: mid-slope roads (2.09), ridge roads (1.36), and valley roads (1.09). The average unweighted circuity factors were 1.61 for mid-slope roads, 1.21 for ridge roads, and 1.07 for valley roads. This study found that the circuity of the forest road network was most affected by the mountain terrain. In addition, the circuity factor increased with increasing network distance in the mid-slope roads but was not affected by the network distance in ridges and valleys. To improve the efficiency of transportation in the forest road network, it is important to locate the ladings and properly connect with the public road network.

Keywords: forest road circuity; forest road network; network distance; forest transportation

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1. Introduction

Distance is the numerical value by which two objects are physically separated, and travel distance (i.e., network distance) is an important factor in determining the accessibility to any destination in the transport and logistics sector [1]. In most cases, since the network distance is longer than expected [2], various distance analysis techniques were studied to estimate distance more accurately [3–5]. Most studies of distance analysis used a distance estimating function based on the Euclidean distances of two points [1,3,5–7].

The circuity factor of a road network, which is one of these distance estimating functions, is defined as the ratio of the shortest distance to the network distance in the road network for two different points [4,8]. Because the regional circuity factor is influenced by terrain, rivers, facilities, and road density [3], it can be used as an index to compare regional traffic efficiency [9] and spatial characteristics [5,10]. The circuity factor can realistically reflect the actual distance required in various plans [3]. For example, the circuity factor for a target area can be calculated accurately after the road is constructed, so that the actual distance of the route to be planned can be estimated using the circuity factor for similar terrain or nearby areas [11].

Studies of road circuity were mainly conducted to identify the characteristics of the network distance on national or urban scales [1,3,5,6] using the weighted circuity factor [1,3,5] or unweighted circuity factor [6]. The aforementioned circuity factor can be defined as unweighted circuity [5,6]; the weighted circuity is the average value of the circuity factor calculated by dividing the network distance into segments of unit length, which is applied because the circuity factor is affected by the network distance [4]. This can be said to be a concept applied to minimize the effects of measuring distance. The accessibility of public facilities, such as public offices, hospitals, and schools, and spatial characteristics, such as the location analysis of residential space using commuting distance, were compared using circuity factors [3,6]. These circuity factors estimate the actual distance with a certain level of accuracy within the urbanized area [12], and several studies found an average circuity factor of 1.2 to 1.3 in urban road networks [1,3–5,13,14]. However, in the case of non-urbanized areas, the deviation may be large [1,15]. In particular, forest roads, which provide infrastructure for sustainable forest management [16], are affected by their route alignments due to mountainous terrain; thus, most of the route is composed of complex linear shapes, and the circuity factors deviate considerably from region to region [11,15]. To estimate the actual road distance for planning a road network or forest operation, estimating the network distance and calculating the circuity factor of the forest road network are necessary. Through this process, it is possible to more accurately and quickly estimate the transportation time and cost using various forestry machines. As the network distance on the road increases, the transportation efficiency decreases and costs increase; these differences can be used to assess the alignment of the road route in terms of its transportation efficiency.

Several studies reported on the circuity of forest road networks. Although their methods and objects differed (e.g., forest roads, public roads, and railways), their results can be converted into the circuity factor of the forest roads as follows: Sugihara and Iwakawa [17], 1.57; Hujiwara [18], 1.22–1.58; Cha et al. [19], 1.33–1.63; Cha and Cho [20], 1.02–1.88; and Nakazawa et al. [15], 1.29–1.87. These studies reported that the effects of the circuity factor on plane factors (e.g., villages, forests, and streams) are greater than those of stereoscopic factors, such as elevation [1,3,17]. The circuity factor appears higher in areas with rough terrain and rocky areas [20]. Hujiwara [18] reported that the circuity factor of mid-slope roads was higher than that of valleys because mid-slope roads are more affected by the terrain and moving distance than valleys. Nakazawa et al. [15] also analyzed the circuity of road networks (e.g., highways, forest roads, and skid trails) and reported that circuity is influenced by road length, whereas the influence of the longitudinal slope is relatively small. As mentioned above, these studies related to forest road circuits were conducted locally on a single route. Research on such routes is lacking; thus, it is difficult to estimate how many forest road routes are generally bypassed compared to straight-line distances.

Thus, the purpose of this study was to determine how much the road distance differs from the Euclidean distance in mountainous areas. More specifically, this study (1) estimated the average circuity factor for 27 forest roads according to the vertical locations of the roads in South Korea, and (2) analyzed the factors affecting the circuity of forest roads.

2. Materials and Methods

2.1. Study Sites

The 27 forest roads that were randomly selected (about 105 km) are located in the national forests of the Republic of Korea (Figure 1). The study divided each road into its ridge, mid-slope, and valley parts according to the vertical position where the route was located on the mountain slope. The ridge roads are the route section where the vertical height of the slope is over 70%; the mid-slope roads are the section where the vertical height of the slope is between 41% and 70%; the valley roads are defined as a section along a valley with a slope of less than 40% [21]. Finally, the number of forest roads in this study included nine ridge routes (about 38.3 km), 10 mid-slope routes (about 45.0 km), and eight valley routes (about 21.6 km) based on vertical distribution (Figure 1, Table 1).

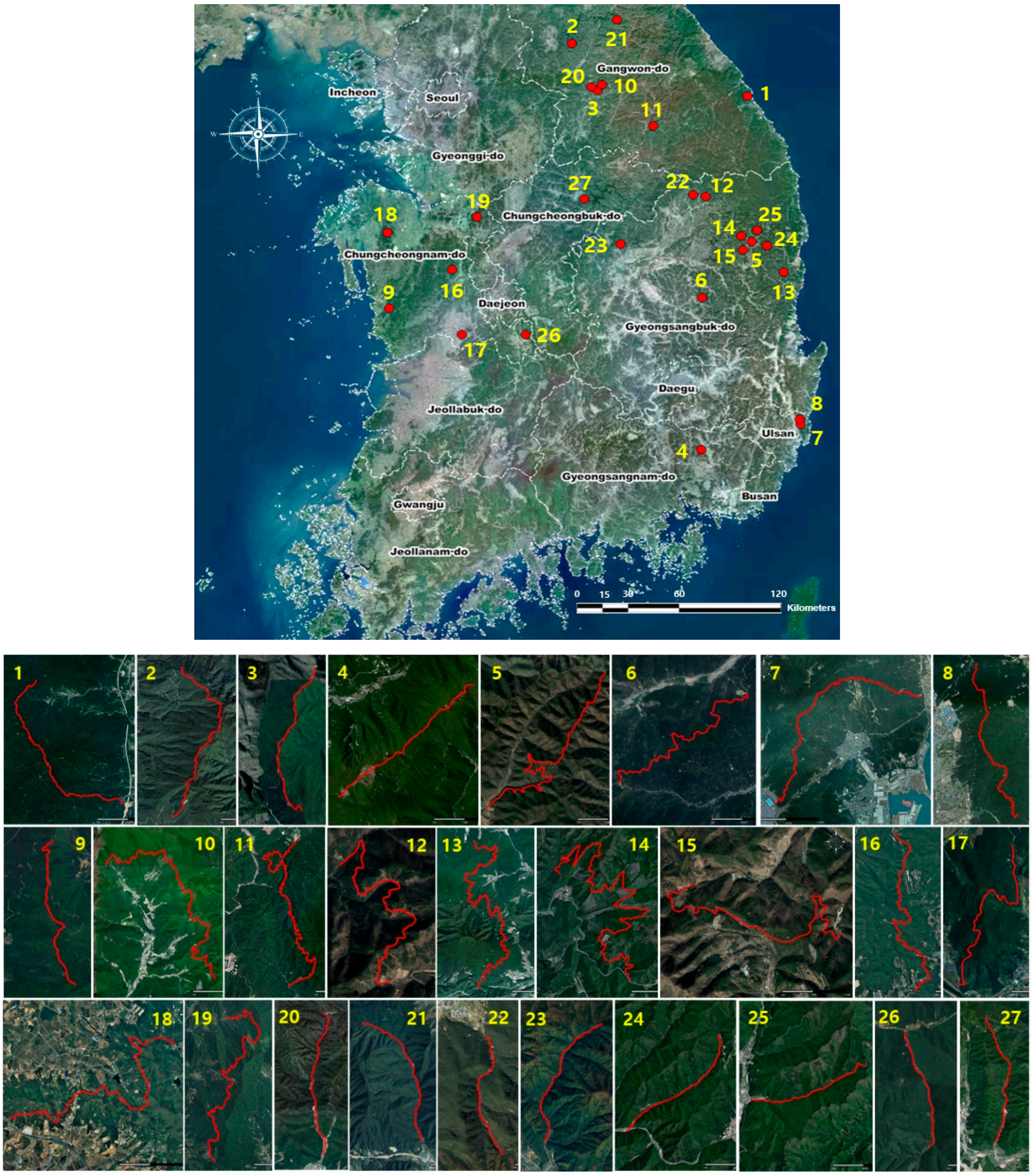

Figure 1. Road location and alignment of the studied routes in the Republic of Korea.

2.2. Computation of Circuity Factors

The circuity of the road is expressed using several measures depending on the scale or purpose of the object. The most representative of these measures are the circuity rate [11,17–20] and the circuity factor [1,3–10]. The computation methods used for expressing road circuity differ, but their concepts are the same. Since the network distance on a forest road has a value greater than the straight-line distance [3], this study used a circuity factor with a value of one or higher, as it can more intuitively express the degree of the road circuity. Then, the circuity factors were calculated using Equation (1).

$$C = \frac{D_{net}}{D_{euc}}, \tag{1}$$

where C is the circuity factor in a given section of forest road route, and D_{net} and D_{euc} are the network and Euclidean distances between the two end-points in a given section of forest road route, respectively.

This study also used calculations to determine the change in the circuity factor every 500 m of road length from the beginning point of the studied roads. Some authors [17,18] calculated the forest road circuity by dividing the network distance into arbitrary sections (e.g., 500 m or 1000 m) to eliminate or minimize the influence of the road's length on the circuity factor, such as unweighted circuity factors [6]. The mean and standard deviation of the circuity factor according to the vertical location (ridge, mid-slope, and valley) were calculated by dividing the route into 500-m sections. Finally, the circuity factors were calculated for 202 sections: 74 sections from the nine ridge routes (about 38.3 km), 88 sections from the 10 mid-slope routes (about 45.0 km), and 40 sections from the eight valley routes (about 21.6 km). For estimating the network distance, firstly, the centerline of the 27 studied roads was digitized using satellite images provided by Google Earth (Google LCC, Mountain view, CA, USA) and polylines of the road routes were created. These lines were used to measure the distance and the Euclidean distance on a two-dimensional plane. Then, all studied routes were digitized by one person to minimize the errors that can occur (according to the manufacturer). In this study, a scale of 1:5000 was used as the reference map to avoid variation in the accuracy according to the scale of the imagery. All spatial analysis was performed using QGIS 2.18 (Boston, MA, USA) to estimate the circuity factors of the studied roads.

Table 1. General information of studied forest road routes.

Road No.	Administrative District	Road Length (m) [1]	Elevation (m)		Longitudinal Slope (%) [4]	Vertical Location
			B.P. [2]	E.P. [3]		
1	Donghae, Kangwon	5000	223	261	8.98	Ridge
2	Chuncheon, Kangwon	4779	537	624	15.29	
3	Heongseong, Kangwon	3229	992	1129	6.47	
4	Milyang, Kyeongnam	4417	721	1077	10.98	
5	Yeongyang, Kyeongbuk	5000	255	462	9.56	
6	Uiseong, Kyeongbuk	3384	171	271	4.31	
7	Bukgu, Ulsan	5000	128	218	9.54	
8	Bukgu, Ulsan	5000	286	389	10.54	
9	Boryeng, Chungnam	2512	202	498	11.84	
10	Heongseong, Kangwon	5000	720	853	9.96	Mid-slope
11	Pyeongchang, Kangwon	5000	323	638	16.44	
12	Bonghwa, Kyeongbuk	2444	405	523	7.65	
13	Yeongdeok, Kyeongbuk	5000	798	813	8.30	
14	Yeongyang, Kyeongbuk	3742	459	455	6.23	
15	Yeongyang, Kyeongbuk	5000	378	420	9.16	
16	Gongju, Chungnam	5000	291	399	5.06	
17	Nonsan, Chungnam	3835	58	159	7.83	
18	Dangjin, Chungnam	5000	78	142	7.32	
19	Cheonan, Chungnam	5000	203	360	10.70	
20	Inje, Kangwon	4273	635	963	12.98	Valley
21	Heongseong, Kangwon	2511	392	685	12.20	
22	Bonghwa, Kyeongbuk	4593	167	325	8.42	
23	Munkyeong, Kyeongbuk	1861	436	654	20.47	
24	Yeongyang, Kyeongbuk	2247	586	750	11.80	
25	Yeongyang, Kyeongbuk	1826	501	746	8.60	
26	Geumsan, Chungnam	1743	350	433	10.93	
27	Chungju, Chungbuk	2556	323	480	8.84	
Total	-	104,952				-

[1] Road length is the distance digitized from the satellite image. [2] Beginning point. [3] End point. [4] The average value of the longitudinal slope of each 500-m section on all routes.

2.3. Factors Affecting the Forest Road Circuity

In this study, three factors that were expected to affect the circuity factors of forest roads were quantitatively analyzed. The first was the road alignment. The number of curved sections (500 m each) and the intersection angles of the curved sections (°) were calculated for each 500-m section of each route. Here, the division of the curved section was defined as a curve when the intersection angle was

155° or less according to the forest road facility standard of the Korea Forest Service [22]. Secondly, many changes occur in the longitudinal curves of forest roads that are constructed in a line shape in a rugged mountainous area. To consider the longitudinal slope, the average longitudinal slopes were calculated for each 500-m section. Thirdly, the shape index [23] of the forested area where the studied routes were constructed was calculated. Because forest roads are essential facilities for forest management, there is a possibility that the route will be further detoured depending on the shape of target area. Therefore, the shape of target area where forest roads are constructed may affect the layout of forest road. The shape index is a constant expressed as the ratio of the area to the circumference length [24]. If the shape is circular, the shape index is 1 (i.e., the smallest perimeter in a given internal area). If the shape is a square, the shape index is 1.13 [16]. The shape index can be expressed by Equation (2).

$$D_i = \frac{p}{2\sqrt{A\pi}}, \tag{2}$$

where D_i is the shape index, p is the perimeter (m), and A is the area size (m^2).

2.4. Statistics

This study conducted a one-way ANOVA and Tukey's honest significant difference (HSD) multiple comparisons test to investigate whether the circuity factors of the vertical distributions of the forest roads (e.g., ridge, mid-slope, and valley roads) were statistically significant ($p < 0.05$). This study also analyzed the correlation between the number of curves, the size of the intersection angle, the average longitudinal slope of the road at 500-m intervals, and the shape index of the study area.

3. Results

3.1. Circuity Factors Vary with Cumulative Network Distance at the Vertical Position of Forest Roads

The average circuity factor of the 27 forest roads was estimated to be 1.55. The average circuity factors differed with the vertical position: 1.36, 2.09, and 1.10 for the nine ridge routes, the 10 mid-slope routes, and eight valley routes, respectively (Figure 2). These results indicate that the network distance of the forest road was about 1.36 times the straight-line distance in the ridges, about 2.1 times the straight-line distance in the mid-slopes, and about 1.1 times the straight-line distance in the valleys.

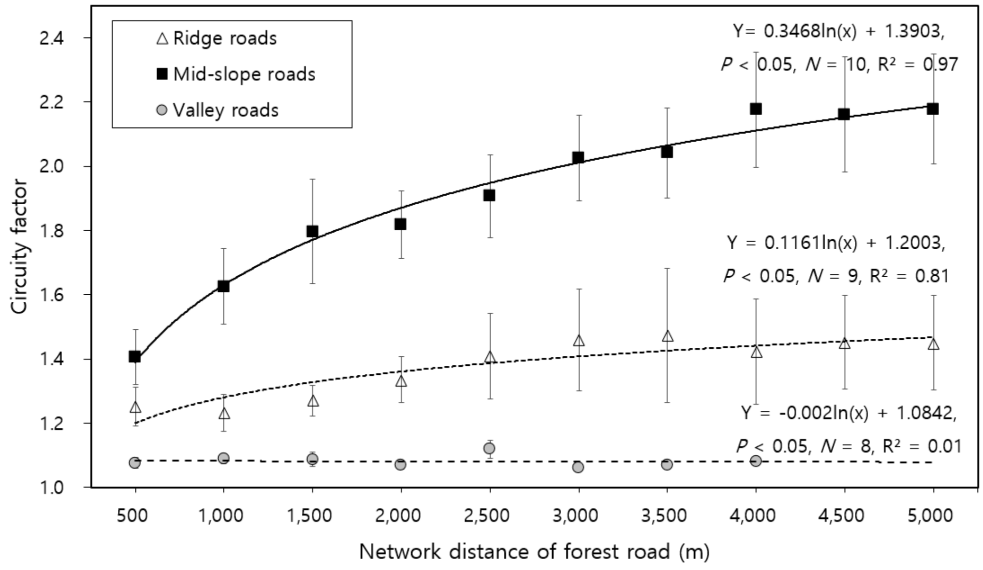

Figure 2. The distribution of the cumulative circuity factors according to the network distance by forest road location.

As a result of estimating the changes in the circuity factors according to an increase in the network distance from 500 m up to the maximum extension (5000 m) of the studied roads, the circuity factor changes of the forest roads showed different patterns depending on ridges, mid-slopes, and valleys (Figure 2). As the measured distance of the forest roads increased from 500 to 5000 m, the circuity factor of the mid-slope roads steadily increased from about 1.41 to 2.21, but the circuity factor of the ridge roads increased steadily up to the measured distance of 3500 m, then declined somewhat. The circuity factor of the valley roads remained in the range of about 1.05 to 1.12 and did not tend to increase even as the network distance increased.

3.2. Circuity Factors in 500-m Interval Sections per Vertical Position of Forest Roads

The weighted average circuity factor in the 500-m sections of the studied roads was the highest in the mid-slope roads (1.61), followed by ridge roads (1.24) and valley roads (1.06) ($p < 0.01$; Table 2).

Table 2. Computation of the circuity factors on forest roads and the results of the one-way ANOVA test per the vertical location of the studied roads.

Vertical Location	Road No.	500-m Section Average Circuity Factor	Mean	SD [1]	F	p
Ridge road (n = 74)	1	1.16 (n = 10)	1.24^{a}	0.328	3.041	<0.01
	2	1.18 (n = 9)				
	3	1.08 (n = 6)				
	4	1.14 (n = 8)				
	5	1.58 (n = 10)				
	6	1.36 (n = 6)				
	7	1.19 (n = 10)				
	8	1.12 (n = 10)				
	9	1.19 (n = 5)				
Mid-slope road (n = 88)	10	1.64 (n = 10)	1.61^{b}	0.482		
	11	1.50 (n = 10)				
	12	2.12 (n = 4)				
	13	1.69 (n = 10)				
	14	1.82 (n = 7)				
	15	1.54 (n = 10)				
	16	1.46 (n = 10)				
	17	1.39 (n = 7)				
	18	1.46 (n = 10)				
	19	1.73 (n = 10)				
Valley road (n = 40)	20	1.05 (n = 8)	1.06^{c}	0.057		
	21	1.05 (n = 5)				
	22	1.09 (n = 9)				
	23	1.13 (n = 3)				
	24	1.04 (n = 4)				
	25	1.03 (n = 3)				
	26	1.03 (n = 3)				
	27	1.04 (n = 5)				

[1] SD: Standard deviation. Superscript letters (a, b, and c) represent a significant difference at $\alpha = 0.01$.

3.3. Correlation between Circuity and Each Influential Factor

The curves in each 500-m section of the studied roads were most frequent (6.1–14.7; mean 9.83) in the mid-slope routes, followed by 2.3–8.1 (mean 6.08) on the ridges; the lowest curve frequency was 1.3–5.8 (mean 2.45) in the valleys (Figure 3). In other words, the curve frequency and the circuity factor were positively correlated in the 500-m sections of the forest road (coefficient of determination (R^2) = 0.79). The intersection angles of the 500-m sections of the forest road were 129°–140° (mean 135.2°) on the mid-slope roads, which had the highest circuity factor. The ridge roads were 129°–146° (mean 140.7°), and the intersection angles of the valley roads, with the lowest circuity factor, were 135°–153° (mean 145.6°). However, the size of the intersection angle in each 500-m section of the forest road was found to be negatively correlated with the circuity factor in the 500-m sections (R^2 = 0.39). The average longitudinal slope of the measurement section was 4.9%–21.4% (mostly within 15%), but the longitudinal slope and circuity factor of the forest roads were not significantly correlated (R^2 = 0.14). The shape index of the study area had a relatively long form due to the large index value for ridge and valley routes with low circuity factors. The shape index of the study area was high for the ridge and valley roads with low circuity factors; Figure 3d shows that this shape index had a longer shape like a bar-type.

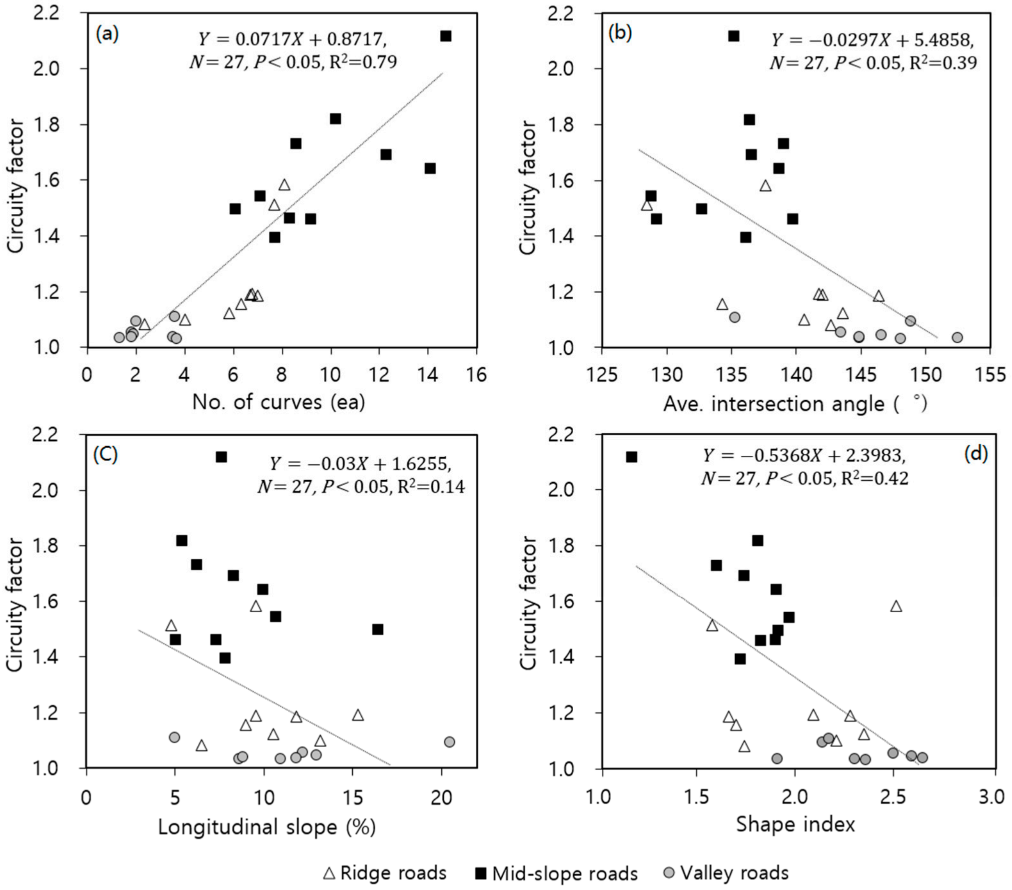

Figure 3. Linear correlation between the circuity factors and influential factors according to the studied road routes in South Korea. Regression between the circuity factor and (**a**) the average number of curves, (**b**) the intersection angle, and (**c**) the longitudinal slope of the 500-m section of the road routes; (**d**) regression between the circuity factor and the shape index.

4. Discussion

As a result of this study, it was found that forest roads in South Korea exceed the Euclidean distance by about 1.6 times on average: ridge roads by about 1.4 times, mid-slope roads by about 2.1 times, and valley roads by about 1.1 times, according to the location of the mountain slope. The average circuity factor of the public road network in South Korea is 1.26 [1]. Compared with the results of this study, the circuity factor of valley roads was lower than that of public roads, whereas those of ridge roads (1.36) and mid-slope roads (2.09) were higher.

In terms of unweighted circuity [6], the circuity factors of the mid-slope roads tended to increase gradually with increasing network distance. The circuity factor of the studied routes was affected by the network distance in the general mountainous area. In particular, in the case of ridge roads, the circuit factor no longer increased in the section above 3500 m, because the average curve of the 500-m section was higher in the sections below 3500 m (mean 6.6) than the sections over 3500 m (mean

4.6). For the studied ridge and valley routes, the circuity factor was also low and the change range was small since the road alignment was relatively straight. Hujiwara [18] reported a similar trend as found in this study. They found about a 30% difference between the mid-slope and valley roads due to changes in the mountain terrain. However, Cha and Cho [20] reported that the circuity of the forest roads is affected by the frequency of valleys and streams but is not correlated with network distance. These results are different from the results of this study because the measurement length of their road circuity was too short (100–300 m) and their study route was locally selected.

Although directly comparing public road networks with forest road networks is difficult because public roads are longer than forest roads, the circuity factor of the public road networks is known to gradually decrease as the network distance traveled increases [1,6]. According to Kim et al. [1], the circuity of public road networks, including highways in South Korea, gradually increases to about 100 km of traveled distance and then tends to decrease. Other studies considered the increase of circuity to be caused by the influence of topography and other avoidance factors within relatively short sections (within 100 km); thereafter, circuity decreased due to the influence of the form of the route, that is, straightened wide-area networks, such as highways or the national road system. The road alignment is highly affected by the terrain; the linearity of this alignment can be achieved using tunnels and bridges, whereas forest roads are more influenced by changes in the mountain terrain. Therefore, the transportation efficiency of the forest roads in mountainous areas decreases as the network distance increases.

In terms of the weighted circuity based on 500-m sections, the average circuity factor was 1–1.6 times higher than the straight distance. Most studies on forest road circuity [15,17–20] estimated the weighted circuity factors based on different interval distances. Although difficult to compare, Cha and Cho [19] and Cha et al. [20] reported that the average circuity of the forest roads in some areas of South Korea bypassed the average by 1.2–1.6 times compared to the straight-line distance. Hujiwara [18] found that the average circuity of mid-slope roads (1.58) was higher than that of valleys (1.21), indicating a similar trend. A number of studies reported that the circuity of road networks is influenced by the shape of the road network, which is affected by planar and vertical factors [1,3]. In particular, the horizontal alignment that affects the circuity of road networks is more influenced by the planar factor than the vertical factor [1,3,15] and depends on the shape of the mountainous terrain and the frequency of ridges and valleys [19,20]. For road networks on national scales, circuity is affected by multiple factors, such as the sample size of the city, road density and connectivity, lakes and seas, mountains, and conservation areas [3].

The results of this study show that the road circuity is considerably influenced by the change in mountainous terrain. In mid-slope areas, roads are commonly constructed along the contour line at an average slope of less than 10% to prevent longitudinal erosion that may occur along the road's surface and the periphery along the route [25]. The mid-slope roads on these gentle gradients repeatedly pass through ridges and valleys; thus, the horizontal alignment of the lines has a winding shape. Therefore, the road routes detour further, and this is why mid-slope roads have a network distance about 1.6 times the straight-line distance based on the road's beginning and end points. In whole-tree harvesting sites, it is important to build multiple log landings to increase transport efficiency [26]. In general, the pre-hauling of ground-based harvesting is performed within the 500-m range [27]. Therefore, ground-based pre-hauling using forest roads or skid trails can be applied in terms of weighted circuitry. On the other hand, estimates of timber transport distances using log trucks may apply unweighted circuity.

The circuity factors of ridge and valley roads were relatively low, and their variations were not large. These results indicate that the road alignments on ridges and in valleys were relatively straight compared to those of the mid-slope roads. The ridge and valley areas are thought to be less developed; I determined that few route detours occur because the routes in the mountain area pass through the ridges with a relatively small change. Consequently, the circuity of this route appeared to be low. The valley roads are constructed in mountainous areas where the development of ridges and valleys is remarkable. However, since this route has a gradient that builds relatively rapidly along the direction of the water system, I found less circuity than the mid-slope roads.

The proportion of seven or more curves in the planar line of the study route was about 77% for mid-slope, about 41% for ridge, and 10% for valley routes. This shows that the topographical changes in the mid-slope roads are relatively larger than those of the ridges and the valleys. In particular, the horizontal alignment of the route determines the curves and intersection angle depending on the shape of the terrain [20]. The circuity of the forest road increases as the number of curves increases, and the intersection angles decrease. Even with the same frequency of curves, the circuity factor of the mid-slope roads was larger than the other sections, which is why the intersection angles of the mid-slope roads were smaller. The correlation coefficient between the weighted circuity factor (500-m intervals) and the average longitudinal slope was low, but the shape index was relatively bar-shaped in the area with a low degree of circuity. This is because the road route was arranged to evenly cross the target area. Thus, the horizontal alignment of the route has a close relationship with the mountainous terrain; these factors were shown to considerably influence the road circuity.

5. Conclusions

Road alignment plays a crucial role in ensuring the safety and smooth travel of a vehicle. However, since most roads have irregular and winding linear shapes due to rough and complicated terrain conditions, their speed is limited to ensure the safety of the traveling vehicle, which considerably influences transportation efficiency.

As a result of this study, the forest roads in the mountainous areas of South Korea were found to exceed the Euclidean distance by an average of 1.1–2.1 times, and the most detours occur on mid-slope roads. This study concludes that road circuity has a close relationship with mountainous terrain, and the changes in the mid-slope terrain are relatively larger than those of ridge or valley terrains. It was found that road circuity increases as network distance increases in mountainous areas; a longer route length of the road results in a lower efficiency of transport through the road network. To increase the efficiency of forest operations and transportation, it is important to locate the landings and properly connect them with public road networks.

The circuity of public road networks on the national and regional scales is somewhat different from the circuity of forest road networks. Since this circuity depends on various factors, including its measurement distance and method, a suitable method for estimating the circuity of forest roads is required. In the future, it is expected that it will be possible to use various aspects, such as the evaluation of the transportation efficiency of road networks, to estimate the network distance of planning routes and engage in operation planning.

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