land

Article

Factors Affecting Earthwork Volume in Forest Road Construction on Steep Terrain

Ivica Papa [1], Rodolfo Picchio [2,*], Mihael Lovrinčević [1], David Janeš [1], Tibor Pentek [1], Dino Validžić [3], Rachele Venanzi [2] and Andreja Đuka [1,*]

[1] Department of Forest Engineering, Faculty of Forestry and Wood Technology, University of Zagreb, Svetošimunska Cesta 23, 10 000 Zagreb, Croatia
[2] Department of Agriculture and Forest Sciences (DAFNE), Tuscia University, Via S. Camillo de Lellis, 01100 Viterbo, Italy
[3] Vukovarska Ulica 68, 33 410 Suhopolje, Croatia
* Correspondence: r.picchio@unitus.it (R.P.); aduka@sumfak.unizg.hr (A.Đ.)

Abstract: Forest roads, as a prerequisite for high-quality forest management, should be optimally distributed in order to avoid negative environmental impacts and to best fulfill their task. In the design phase of forest roads, it is necessary to know which factors influence most the volume of earthworks to enable the designer to best adapt to the terrain requirements. In this paper the impact of an average cross terrain slope and carriageway value of a forest road on cut and fill volume is analyzed. The research was carried out in the area of the management unit Trovrh–Kik, characterized by irregular terrain with slopes ranging between 27 and 58%, and on some micro locations even up to 84%. On eight forest roads, based on standard cross-section profiles, the influence of the average cross terrain slope and carriageway value (difference between ground level and grade level) of the forest road on the cut and fill volume per 1 m of the forest road route was analyzed. The obtained coefficients of determination indicate a strong correlation between the cut volume and carriageway value (R^2 = 0.6841), and a moderate correlation between the fill volume and carriageway value (R^2 = 0.5619). Unlike the influence of carriageway value on the cut and fill volume, the correlation between the cross terrain slope and fill volume is weak (R^2 = 0.2076) or moderate in the case of the cut volume (R^2 = 0.3167). On the basis of the analyzed standard cross-section profiles, it was determined that the carriageway value was 0.051 m, where the difference between the cut and fill volume was minimum and the average actual carriageway value was determined to be −0.09 m. It can be concluded that, on terrains with large and varying slopes, there is no unique model or terrain factor that could describe the earthworks required in the construction of a forest road. However, it is beyond doubt that the increase in the carriageway value and cross terrain slope caused the increase in the aforementioned volumes.

Keywords: forest road; construction; cross terrain slope; carriageway value; cut volume; fill volume; steep terrain

check for updates

Citation: Papa, I.; Picchio, R.; Lovrinčević, M.; Janeš, D.; Pentek, T.; Validžić, D.; Venanzi, R.; Đuka, A. Factors Affecting Earthwork Volume in Forest Road Construction on Steep Terrain. *Land* **2023**, *12*, 400. https://doi.org/10.3390/land12020400

Academic Editors: Panagiotis Lemonakis, Apostolos Kantartzis and Chrisovaladis Malesios

Received: 28 December 2022
Revised: 27 January 2023
Accepted: 31 January 2023
Published: 2 February 2023

1. Introduction

A high-quality, regularly planned and evenly distributed forest road network is the basic prerequisite for forest management [1–3]. In order to provide a forest road network of high quality and efficiency, it is extremely important to approach each work phase properly, which is necessary for establishing an optimal forest transport network. According to Pentek et al. [4], establishing an optimal primary forest road network is always carried out through the following working phases: planning, designing, supervised construction and maintenance. According to the same authors [5], along with the above stated, always present, phases of optimization of primary forest traffic infrastructure, sometimes, if required, two other working phases appear—the reconstruction of forest roads and closing constructed forest roads for use. These phases are interrelated and dependent, and they should be carried out in the stated order, taking into account that a new phase cannot be initiated unless the previous one has been satisfactorily completed. The importance and complexity of this type of work is also reflected in the fact that in the market there are many guidebooks, primarily intended for private forest owners, which contain guidelines for the optimal management of forest traffic infrastructure. The mentioned guidebooks contain instructions for all phases of establishing a forest road network, with the focus on costs and environmental issues [6–10]. The poor implementation of any of these phases leads to different negative effects of forest roads, the most frequent being the following: changes of stand conditions affecting biodiversity [11–16]; erosion, sedimentation and change in soil characteristics [17–20]; an impact on the water regime and water quality [21,22]; and also a very significant negative perception of people regarding forestry and forest roads [23]. Due to the above (especially in special purpose forests), designers must make great efforts in designing and constructing forest roads [24–26].

After completing the designing phase, the construction phase follows, during which the highest costs are incurred in the whole process of building a new forest road. This is also confirmed by Caliskan [27], who states that forest roads are the most expensive constructions in forestry, while according to Epstein and Sessions [28], the phases of planning, designing and construction of forest roads are the most expensive and the most time-consuming elements in the system of timber harvesting. The complexity of the construction phase of forest roads is best described by Caliskan [27], who emphasizes that the construction of forest roads on mountainous terrain is a risky operation that can cause considerable damage to the landscape and forest ecosystem, unless properly implemented. The construction phase of forest roads, depending on the author, is carried out through several subphases. Douglas [29] divides the construction works into the following subphases: land preparation, excavation, formation of embankments, finishing operations and paving.

Kramer [6] divides the construction of forest roads into clearing and grubbing, earthwork and surfacing, while Ryan et al. [8] mention three key phases in the construction of forest roads: road formation (the phase that includes all earthworks), road drainage and road completion. According to the FAO [30] classification, forest road construction works can be divided into clearing and piling, earthwork, finishing grading, surfacing and drainage, which is in line with the classification in force in the Republic of Croatia, where, according to the rulebook [31], the forest road construction works are divided into preparatory works, soil improvement, lower structure works, upper structure works, surface and underground drainage facilities, construction of bridges and other forest traffic infrastructure facilities. The last classification was the one used for defining measures and cost estimates of the forest roads analyzed in this paper.

Regarding cost estimates of forest road construction, i.e., the factors affecting the estimated cost of different components during the phase of road construction, we can say that this is a very challenging task, further complicated by environmental restrictions reflected in varying topography, the presence of different types of soil on the forest road route and varying shares of rockiness [32,33]. Pearce [34] studied the importance and the amount of costs spent for the construction and maintenance of the forest road infrastructure, and he claims that the highest expenditure in total costs of timber production is related to the construction and maintenance of the forest traffic infrastructure. The same is confirmed by Martinić [35], who states that the costs related to the cutting, felling and transport of timber, as well as the costs for the construction and maintenance of forest traffic infrastructure, account for 59% of the total sale price of timber.

Analyzing the total costs of forest road construction, Sessions [36] states that there are six key cost items that are considered influential, namely the costs for: construction staking, clearing and piling, earthwork, finishing grading, surfacing and drainage. A detailed analysis of the share of individual types of costs in the total cost of forest road construction was made by [37]; they concluded that one of the most important factors affecting the cost of forest road construction on steep (mountainous) terrain is the cost of earthwork cuts, amounting to up to 80%. Therefore, the assessment of earthwork volume is indispensable for planning the cost of a forest road construction, as well as for minimizing damage to the forest ecosystem. In the past, many authors have dealt with the influencing factors requiring earthworks during the phase of forest road construction. Thus, assuming a uniform terrain slope, Jeličić [38] develops a model for calculating the surface of cross-sections (calculation of the surface of the cut and fill volume) for different cross terrain slopes using the carriageway value, pavement width and material category as independent variables. Potočnik [39] analyzes the cutting of the road into terrain, i.e., the dependence of the carriageway value and cross terrain slope. The author concludes that with the increase in the cross terrain slope, the carriageway value also increases, and states that it is necessary to increase the carriageway value on steep terrain so that the vehicles moving on the road can keep all wheels on the ground. He emphasizes that this is very important for the stability of the forest road and for the rationalization of construction costs, because in such cases there is no need for the additional soil stabilization of embankment slopes. Additionally, when analyzing the data of cross-section profiles, Sokolović and Bajrić [40] determined the correlation between cross terrain slope, carriageway value and earthwork volume. The authors carried out an analysis on terrains of different categories, "C" (all materials that require no mining) and "A" (all solid materials), and the obtained results of the regression equations indicate an increasing trend of earthwork volume with an increase in cross terrain slope. The authors also found that the dependence of earthwork volume on cross terrain slope or the carriageway value was higher with material of category "C" and conclude that the obtained regression equations can only be used as a rough indicator of the cut volume, while the exact earthwork volume can only be determined based on field measurements and cross-section profiles. The General Technical Requirements for Road Works [41] describe three basic categories of construction material in Croatia:

- material of category "A" comprises all solid materials, where mining is required in the case of whole cuts;
- material of category "B" comprises medium-solid rocky soils, where partial mining is required, while the remaining cut is carried out by machinery;
- material of category "C" comprises all materials that require no mining and can be dug directly by use of proper machinery—a bulldozer, excavator or scraper.

As the use of adequate machines during the construction of forest roads affects the total construction costs [42] and considering the fact that this research was carried out on steep/sloped terrain, it should be emphasized that all analyzed projects were designed for the construction of forest roads with the use of excavators equipped with a hydraulic hammer. The reason lies in the fact that in designing and constructing embankments on steep terrain, there occurs a problem of embankment stability, with the risk of a part or the whole embankment sliding down the slope, and such sliding is among the most severe deformations and can cause the collapse of the forest road [43]. For this reason and with the aim of providing embankment stability on steep slopes, depending on the values of cross terrain slope (α), Jeličić [44] divides the terrain in terms of road construction into four categories, as follows:

1. $\alpha \leq 20.00\%$—embankment safe from sliding;
2. $20.01 < \alpha \leq 50.00\%$—it is necessary to design and construct embankment benching;
3. $50.01 < \alpha \leq 67.00\%$—it is necessary to plan and design retaining walls;
4. $\alpha > 67.01\%$—obligatory construction of retaining walls.

The aims of this paper are as follows:

1. Analyze the impact of an average cross terrain slope and the carriageway value of a forest road (difference between ground level and grade level) on:
    - cut volume per 1 m of forest road route (m^3 per running meter),
    - fill volume per 1 m of forest road route (m^3 per running meter);

2. Establish the possibility of estimating a cross terrain slope based on a non-interpolated digital terrain model (DTM) and interpolated digital terrain model with pixel size 15 × 15 m (we used the value at the nearest points for creating non-interpolated DTM);
3. Define the carriageway value with minimum differences between cut and fill volumes;
4. Determine which field factors take part in earthwork costs and their share in the total cost of a forest road construction.

2. Materials and Methods

2.1. Study Area

The research was carried out in the management unit Trovrh–Kik (Figure 1) situated in Lika and Senj County, Croatia (44°48′26.68″–44°40′44.70″ N and 15°52′53.42″–15°43′58.66″ E) covering an area of 4516.63 ha. In terms of altitude, this management unit is situated between 620 and 1613 m a.s.l. (above sea level). The slopes are different, mainly ranging between 27 and 58%. In some parts, there are plateaus, flat or with a very small slope, while in some micro-locations, the slope is more than 84%.

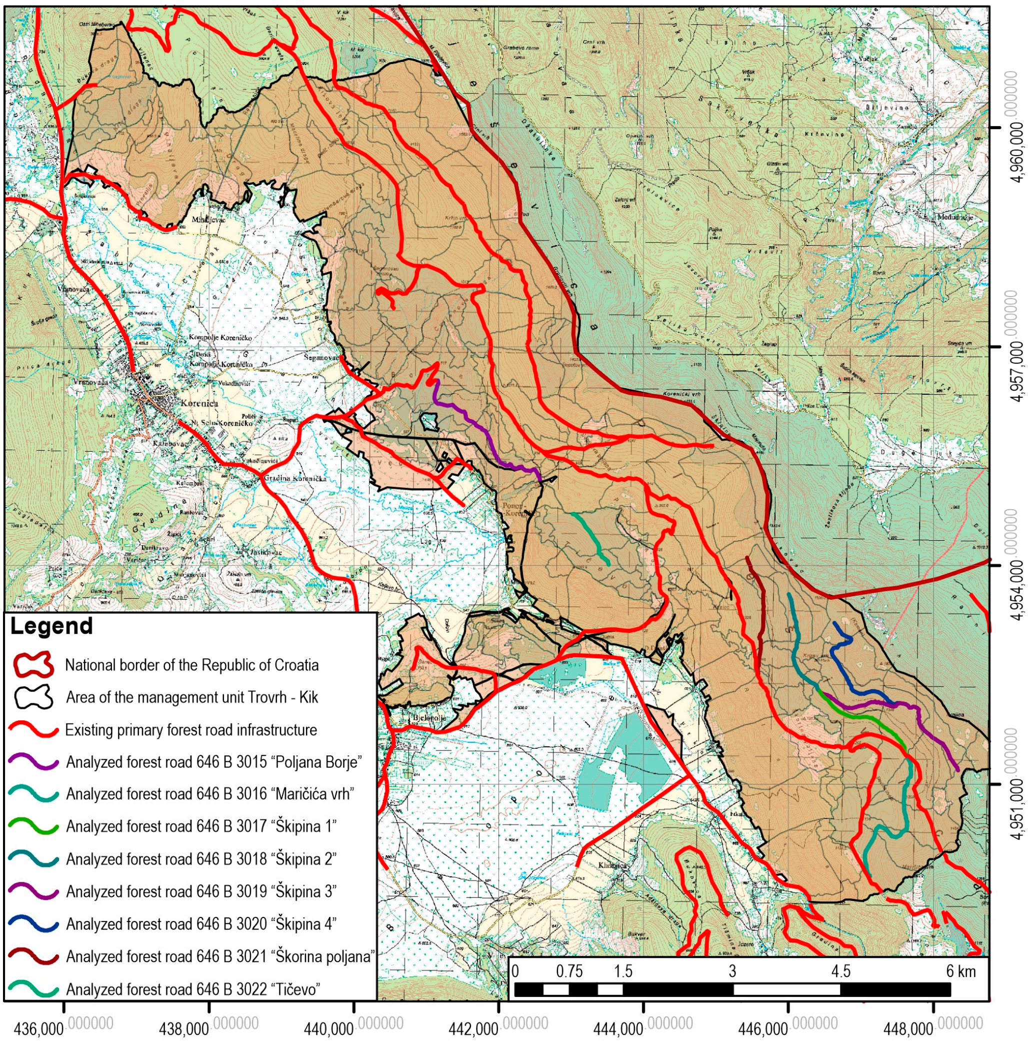

Figure 1. Map of research area.

2.2. Analyzed Data and Used Programs

Within the scope of this research, data of 8 main forest road projects developed by the Faculty of Forestry and Wood Technology, University of Zagreb, in 2018 for the needs of the investor Hrvatske šume d.o.o. (Croatian Forests Ltd., Zagreb, Croatia) were analyzed. All 8 designed roads are situated in the management unit Trovrh–Kik under the management of the forest office Korenica, Forest Administration Gospić; it is important to emphasize that all analyzed forest roads are newly planned and designed with the aim of enabling accessibility to inaccessible forest areas. The actual road density is 10.71 km/1000 ha, with an average timber extraction distance of 346 ± 281 m, while the improved conditions after the construction of the newly planned primary forest traffic infrastructure will be 12.99 km/1000 ha, with an average timber extraction distance of 285 ± 252 m. It should be noted that all 8 main forest road projects included in this research were made in the computer program »Cesta« (Road), developed by the Slovenian company »Softdata«. This is currently the official computer program for designing forest roads in the Republic of Croatia, and the projects were designed by the same person so as to minimize the influence of the designer's style and habits on study parameters. Forest road codes, forest road names, stationing and the total number of analyzed profiles are presented in Table 1. The codes of the forest roads have been made in accordance with the applicable methodology for making a registry of primary forest traffic infrastructure used in the Republic of Croatia [45].

Table 1. Forest road stationing and number of total/analyzed profiles.

Forest Road Code	Forest Road Name	Stationing (hm)	Number of Profiles in Total	Number of Analyzed Profiles (Pavement Width 3.5 m)
646 B 3015	"Poljana Borje"	23 + 43.44	257	162
646 B 3016	"Maričića vrh"	23 + 07.50	231	167
646 B 3017	"Škipina 1"	15 + 99.85	163	134
646 B 3018	"Škipina 2"	15 + 13.43	161	138
646 B 3019	"Škipina 3"	25 + 38.89	266	198
646 B 3020	"Škipina 4"	20 + 11.00	211	157
646 B 3021	"Škorina poljana"	16 + 71.57	167	134
646 B 3022	"Tičevo"	08 + 93.55	90	63
TOTAL		148 + 79.23	1546	1153

Stationing (hm) describes the distance of any given profile from the first profile of the road (1 hm = 100 m).

Field data were collected during classical terrain surveying using a theodolite South ET-02 for measuring horizontal lines, and a levelling instrument GEOALLEN DSZ3-32X for measuring vertical lines. For measuring the cross section slope, we used geodetic rods. The first rod was equipped with a measuring tape for reading height differences every two meters of horizontal distance (or less if necessary) and the second rod was equipped with a level for ensuring 2 m horizontal distance. The cross section slope included a measuring cross section profile 8 m wide for each side (16 m in total) for every profile of the forest road. The methodology described was used for field data collection during the stage of forest road designing.

A total of 1153 normal cross section profiles (Table 1) were processed. All analyzed profiles had the planned cut slope in a ratio of 2:1, the planned fill slope in the ratio 1:1, a constant pavement width of 3.5 m, a constant road shoulder width of 0.5 m and trapezoidal drainage ditches in cut sections with a size of 0.30 × 0.30 × 0.90 m (Figure 2). Additionally, for each analyzed normal cross section profile, the estimated material category was recorded in accordance with [41]. The absolute and percentage shares of the individual estimated material categoreis for each analyzed forest road are presented in Results.

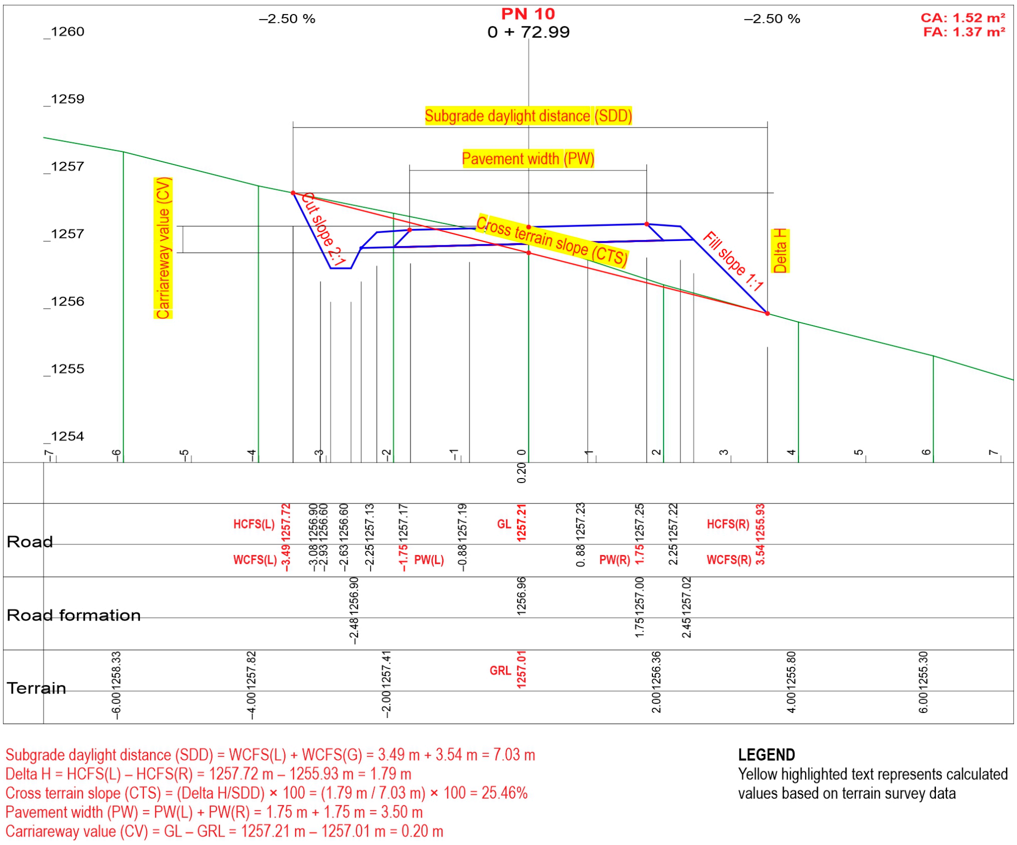

Figure 2. Example of cross section elements used in analysis of cross sectional profile 10, forest road "Maričića vrh".

2.3. Field Data Processing in Microsoft Excel 2016

After the analysis of data provided from the main forest road projects, the database was compiled in the program Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

On the basis of input data from cross-section profiles (Figure 2, Table 2) (number of profile (NP), width of cut/fill slope left (WCFS(L)), height of cut/fill slope left (HCFS(L)), width of cut/fill slope right (WCFS(R)), height of cut/fill slope right (HCFS(R)), pavement width left (PW(L)), pavement width right (PW(R)), grade level (GL), ground level (GRL), cut slope 2:1 (CS), fill slope 1:1 (FS), cut area (CA), fill area (FA)), the parameters presented in Table 2 were calculated (subgrade daylight distance (SDD), Delta H (altitude difference between height of cut/fill slope left and height of cut/fill slope right presented in absolute value), cross terrain slope (CTS), pavement width (PW), carriageway value (CV)). These data required further processing in the program Statistica 14.0.0.15; TIBCO software Inc. Palo Alto, CA, USA.

Each profile will be classified into slope classes according to Jeličić (44) depending on the value of cross terrain slope, Table 3, Figure 3.

Table 2. Read/analyzed data on example of cross section profiles 8–11 for forest road "Maričića vrh".

NP	WCFS(L) (m)	HCFS(L) (m)	WCFS(R) (m)	HCFS(R) (m)	SDD (m)	Delta H (m)	CTS (%)	PW(L) (m)	PW(R) (m)	PW (m)	GL (m)	GRL (m)	CV (m)	FS	CS	CA (m^3 per Running Meter)	FA (m^3 per Running Meter)
8	3.67	1259.73	3.12	1258.01	6.79	1.72	25.33	1.75	1.75	3.50	1258.88	1258.64	0.24	1:1	2:1	2.00	0.74
9	3.69	1258.95	3.46	1256.84	7.15	2.11	29.51	1.75	1.75	3.50	1258.04	1257.88	0.16	1:1	2:1	2.36	1.13
10	**3.49**	**1257.72**	**3.54**	**1255.93**	**7.03**	**1.79**	**25.46**	**1.75**	**1.75**	**3.50**	**1257.21**	**1257.01**	**0.20**	**1:1**	**2:1**	**1.52**	**1.37**
11	3.34	1256.73	3.74	1255.04	7.08	1.69	23.87	1.75	1.75	3.50	1258.52	1255.89	2.63	1:1	2:1	0.58	2.68

Yellow highlighted text represents calculated values based on terrain survey data and the red bold text represent values graphically shown in Figure 2.

Table 3. Share of analyzed profiles by slope classes.

Slope Class	Number of Analyzed Cross Sections	Share of Slope Class (%)
1 (<20.00%)	67	5.81
2 (20.01–50.00%)	806	69.90
3 (50.01–67.00%)	257	22.29
4 (>67.01%)	23	1.99

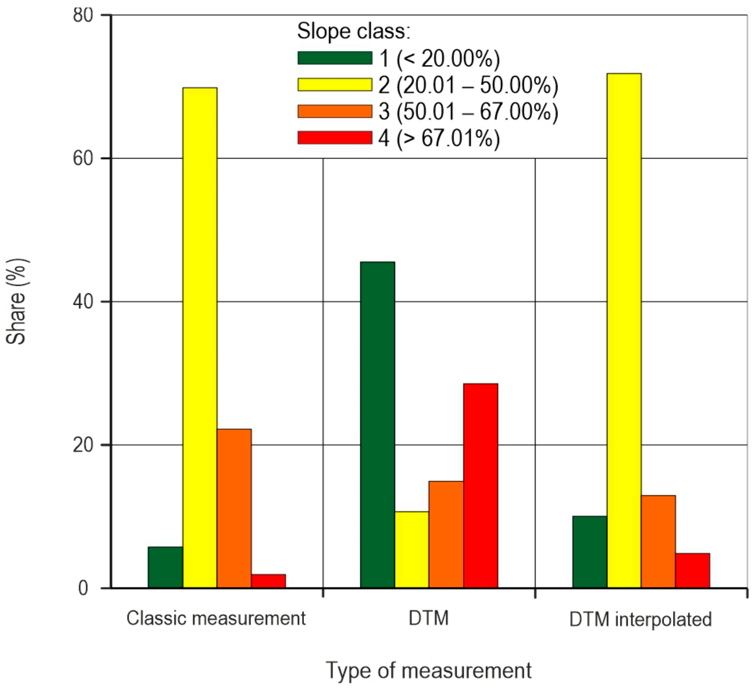

Figure 3. Share of slope class according to type of measurement.

2.4. Field Data Processing in AutoCAD 2022 and ArcMap 10.8

Furthermore, the lines of all analyzed cross section profiles were derived from the computer program »Cesta« (Road) in .dxf form. Their further processing was undertaken in the program AutoCAD 2022 (Autodesk, Inc., San Francisco, CA, USA); using the options "trim"and "extend", profile line ends could be brought into the exact position of contact between embankment feet/cut and ground soil on the left and right of the forest road route.

The arranged profile lines were entered into the program ArcMap 10.8 (Esri, Redlands, CA, USA), where each profile line end received a point, for which the altitude was later determined, on the basis of a digital relief model of the Republic of Croatia with a pixel size of 15 × 15 m. Based on the difference in altitude of the profile line on the left and right, and data on their horizontal distance, the cross terrain slope of each analyzed cross-section profile can be calculated based on the accurateness of a non-interpolated and interpolated digital relief model of the Republic of Croatia with a pixel size of 15 × 15 m. DTM is considered a continuous, usually smooth surface, which, in addition to height values (as DEMs), also contains other elements that describe a topographic surface: slope, aspect, curvature, gradient, skeleton (pits, thalwegs, saddles, ridges, peaks), and others. An interpolated digital relief model of the Republic of Croatia was made in the program ArcMap 10.8 based on non-interpolated digital relief model using the option "bilinear interpolation" within the tool "extract multi values to points". The aforementioned option "bilinear interpolation" uses the value of the four nearest input cell centers to determine the value on the output raster. The new value for the output cell is a weighted average of these four values, adjusted to account for their distance from the center of the output cell. This interpolation method results in a smoother-looking surface than can be obtained using the nearest neighbor test.

3. Results

Based on the processed data and the analysis of all 1153 profiles, the average terrain slope was 41.35%, while the average carriageway value was negative, namely −0.09 m, i.e., the grade level was on average lower that the ground level. The maximum depth of the carriageway value was −2.06 m, and this was recorded on forest road "Maričića vrh" in the 45th profile, while the maximum height of the carriageway value was recorded in profile no. 198 on forest road "Škipina 4", amounting to 1.54 m. The cut volume of earth material ranged from the minimum 0.16 m^3 per running meter recorded in the profile No. 137 on the forest road "Maričića vrh" till the maximum 17.12 m^3 per running meter in profile no. 198 on the forest road "Škipina 3". The average value of the cut volume of all analyzed profiles was 3.47 m^3 per running meter, while the average value of the fill volume of earth material was somewhat lower and amounted to 2.37 m^3 per running meter. The fill volume of 54 observed profiles was 0.00 m^3 per running meter, which means that these were cross-section profiles of full-section or part-section cuts. The maximum fill volume was recorded on the forest road "Škipina 4" in cross-section profile no. 198 and amounted to 14.15 m^3 per running meter. The basic statistical data analyzed are presented in Table 4.

Table 4. Share of analyzed profiles by slope classes.

Statistical Parameters	Cross Terrain Slope (%)	Carriageway Value (m)	Cut Volume (m^3 per Running Meter)	Fill Volume (m^3 per Running Meter)	Difference between Cut and Fill Volume (m^3 per Running Meter)
Arithmetic mean	41.35	−0.09	3.47	2.37	2.79
Median	42.53	−0.09	3.05	1.89	2.18
Modus	0.00	−0.25	1.27	0.00	1.27
Standard deviation	13.16	0.43	2.37	2.06	2.43
Minimum value	0.00	−2.06	0.16	0.00	0.01
Maximum value	91.83	1.54	17.12	14.15	16.97
Number of analyzed profiles	1153	1153	1153	1153	1153

Figure 3 presents the values of cross terrain slope or, to be precise, the distribution of slope classes obtained by the direct measurement of cross-section profiles in the field, i.e., by the analysis of profile lines in the program AutoCAD 2022 and ArcMap 10.8 based on a non-interpolated digital terrain model with a pixel size of 15 × 15 m and interpolated digital terrain model with a pixel size of 15 × 15 m. The graph clearly shows that the interpolated digital model provides more reliable data in estimating the class of the actual cross terrain slopes.

3.1. Impact of Cross Terrain Slope on Earthwork Volume

Based on the analyzed cross sections gathered by field measurements of profiles, an increasing tendency of the cut volume was observed with an increase in the cross terrain slope, with the obtained coefficient of determination R^2 = 0.3167 (Figure 4), which is a moderate correlation between the observed variables according to the Chaddock scale [46].

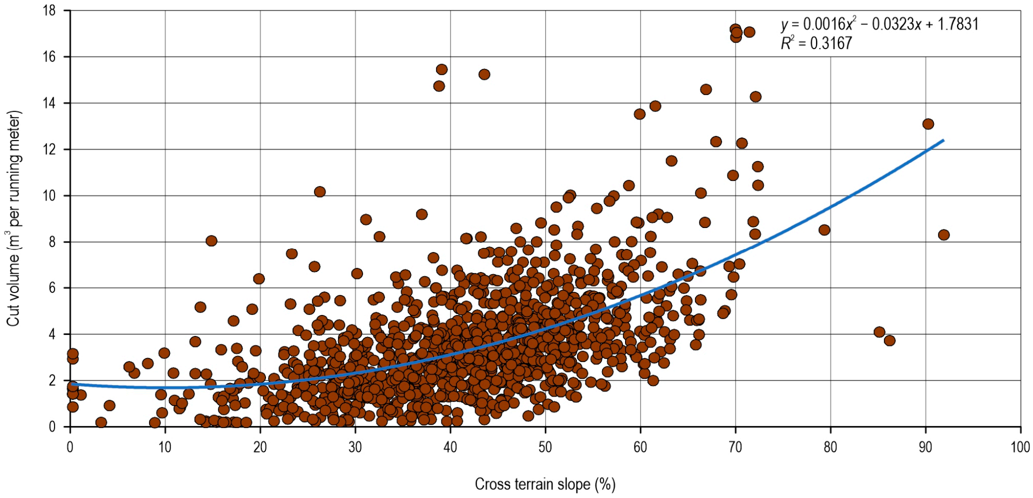

Figure 4. Impact of cross terrain slope on cut volume.

It should be noted that the coefficient of determination between cross terrain slope and fill volume is lower in relation to the dependence of the cut volume on cross terrain slope; it is R^2 = 0.2076 (Figure 5), which is a weak correlation according to the Chaddock scale.

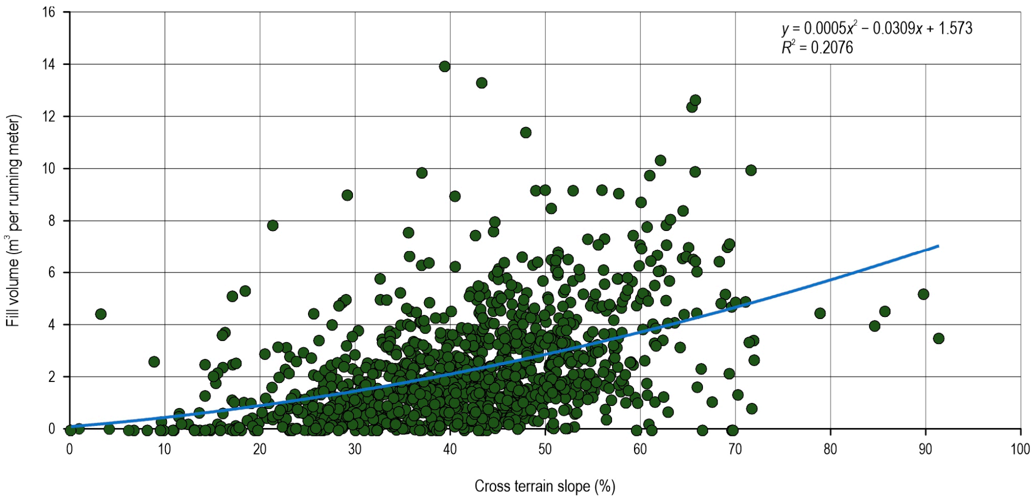

Figure 5. Impact of cross terrain on fill volume.

When the impact of the cross terrain slope on cut and fill volume by defined classes was analyzed individually, coefficients of determination were much lower than was the case when all profiles were analyzed together. The lowest coefficients of determination (R^2) were recorded with cross terrain slope class 4 (>67.01%) and it was 0.0466 for the dependence of the cut volume on cross terrain slope, and only 0.0047 for the dependence of the fill volume on cross terrain slope. The said coefficients of determination, i.e., the observed dispersion of data, are attributed to the small sample size, n = 23, i.e., the small number of analyzed profiles classified into the highest class of cross terrain slope—class 4.

3.2. Impact of Depth of Carriageway on Earthwork Volume

It is beyond doubt that the influence of the carriageway value has a high impact on the earthwork volume on the forest road. The obtained coefficients of determination are higher and correlations are stronger compared with the previous analysis of the impact of cross terrain slope on earthwork volume. The results obtained indicate that the increase in the carriageway value leads to a decrease in the cut volume on the forest road, with the obtained coefficient of determination R^2 = 0.6841 (Figure 6), which is a strong correlation between the observed variables according to the Chaddock scale.

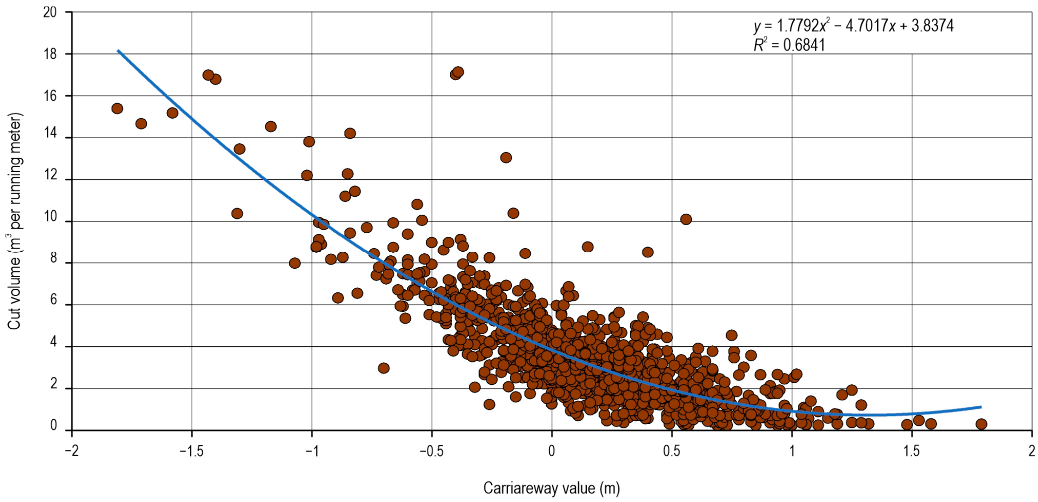

Figure 6. Impact of carriageway value on cut volume.

On the other hand, the increase in the carriageway value leads to the increase in the cut volume on the forest road, with the obtained coefficient of determination R^2 = 0.5619 (Figure 7), which is a moderate correlation between the observed variables according to the Chaddock scale. Similarly to the previous analysis, the coefficient of determination shows a stronger correlation between the carriageway value and cut volume when compared to the correlation between the carriageway value and fill volume.

By the analysis of cross-section profiles by individual slope classes, coefficients of determination were obtained that indicate a strong correlation between the carriageway value and the occurrence of the cut and fill volume during the construction of forest roads on steep terrain. The highest recorded coefficient of determination, R^2 = 0.8346, was established for the correlation between the carriageway value and occurrence of cut volume at slope class 3 (cross terrain slope 50.01–67.00%) and, at the stated slope class, a strong correlation was established between the carriageway value and the occurrence of fill volume R^2 = 0.7767. Similarly to the analysis of the impact of cross terrain slope on the occurrence of the cut and fill volume, this analysis showed that the coefficients of determination are the lowest in slope class 4 (>67.01%) due to a small number of samples n = 23.

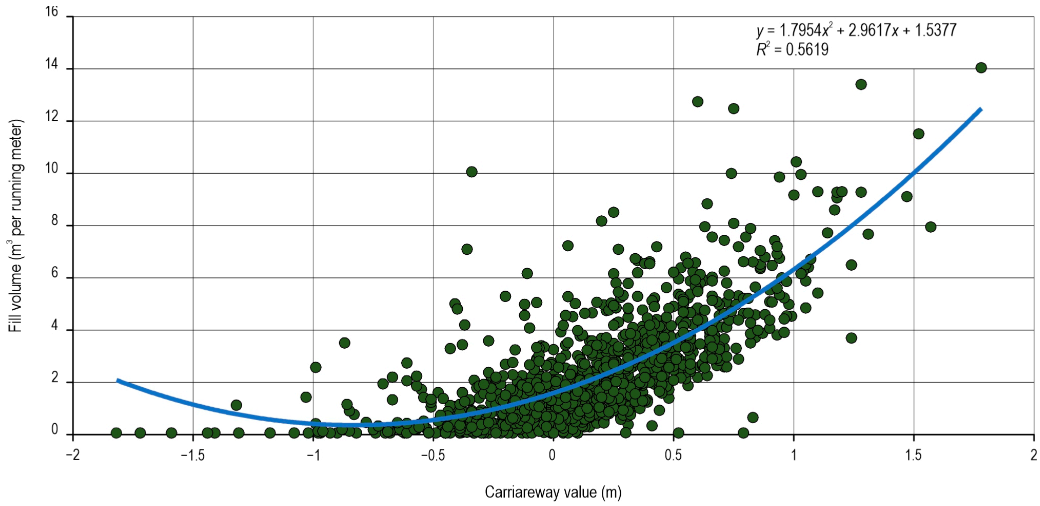

Figure 7. Impact of carriageway value on fill volume.

3.3. Optimal Carriageway Value

Further processing of data dealt with the calculation of differences in cut and fill volumes for each analyzed profile (Figure 8), where again a strong correlation (coefficient of regression R^2 = 0.6681) was observed between the carriageway value and difference in cut and fill volumes of each analyzed profile.

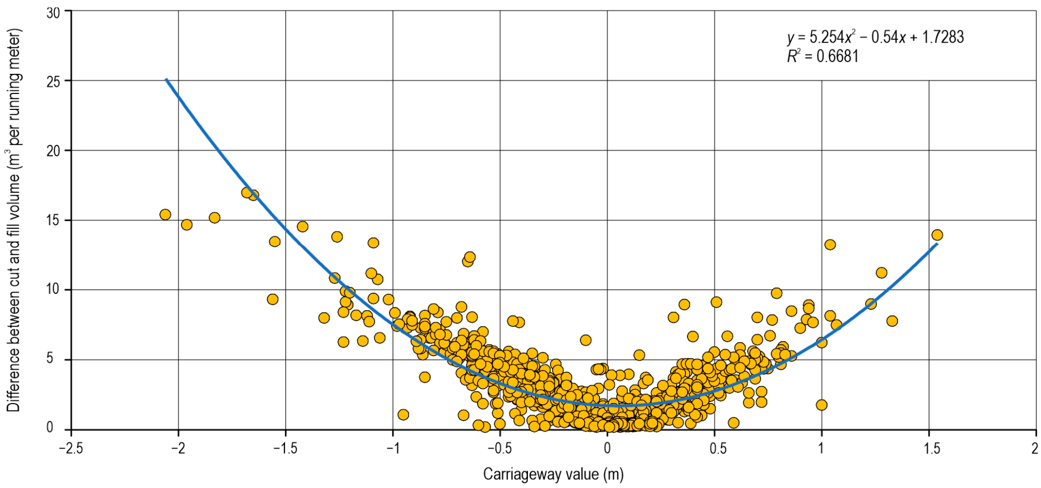

Figure 8. Impact of carriageway value on difference between cut and fill volume.

As the intent of each designer of forest roads is to minimize the difference in cut and fill volumes in each profile, with the aim of minimizing the costs of forest road construction, and consequently also minimizing the adverse effect on the environment, a calculation was made based on the regression equation (Figure 8) of the coordinates of the vertex of the quadratic function with the use of Equations 1 and 2. Further to the above, based on profiles included in the analysis, the optimal carriageway value is +0.051 m, with the differences in cut and fill volumes being 1.714 m^3 per running meter in favor of the fill volume.

$$X_0 = -\frac{b}{2a} \tag{1}$$

$$Y_0 = -\frac{4ac - b^2}{4a} \tag{2}$$

a has a value of 5.254
b has a value of -0.54

c has a value of 1.7283

3.4. Share of Earthwork Cost in Total Cost of Forest Road Construction

Finally, an analysis was made of the influencing factors (cross terrain slope, carriageway value, material category) affecting the share of earthwork costs in the total cost of a forest road construction, because on the analyzed forest roads a very large difference was observed in the share of the mentioned costs, which ranged from the maximum of 74.22% on the forest road "Poljana Borje" to the minimum, 43.63%, recorded on the forest road "Tičevo", in relation to the total cost of construction Table 5.

Table 5. Construction cost by phases.

	"Poljana Borje"	**"Škipina 2"**	**"Škipina 4"**	**"Škipina 1"**	**"Škorina Poljana"**	**"Škipina 3"**	**"Maričića Vrh"**	**"Tičevo"**
Preparatory work (%)	4.93	8.21	7.87	7.16	7.91	7.57	9.03	11.66
Earthworks (%)	64.44	49.97	49.68	52.80	52.26	50.40	46.97	36.24
Drainage system construction (%)	9.79	7.03	5.95	2.64	2.49	3.63	2.88	7.39
* Earthworks ALL (%)	74.22	57.00	55.62	55.44	54.75	54.03	49.85	43.63
Surfacing (%)	20.85	34.79	36.51	37.40	37.34	38.39	41.13	44.71
Arithmetic mean of cross terrain slope (%)	48.33	47.84	44.52	40.43	40.54	42.64	32.12	25.24

* Since the drainage system construction works include the excavation of trapezoidal side ditches we have included those costs in the costs of Earthworks ALL.

When comparing the mean values of the cross terrain slope and the share of estimated earthwork volumes in the total cost of construction of the analyzed forest roads, it can be concluded that with the decrease in cross terrain slope, the share of earthwork cost in the total cost also decreases (Figure 9A), while such a trend was not observed in comparing the carriageway value and the share of earthwork cost in the total cost of construction (Figure 9B).

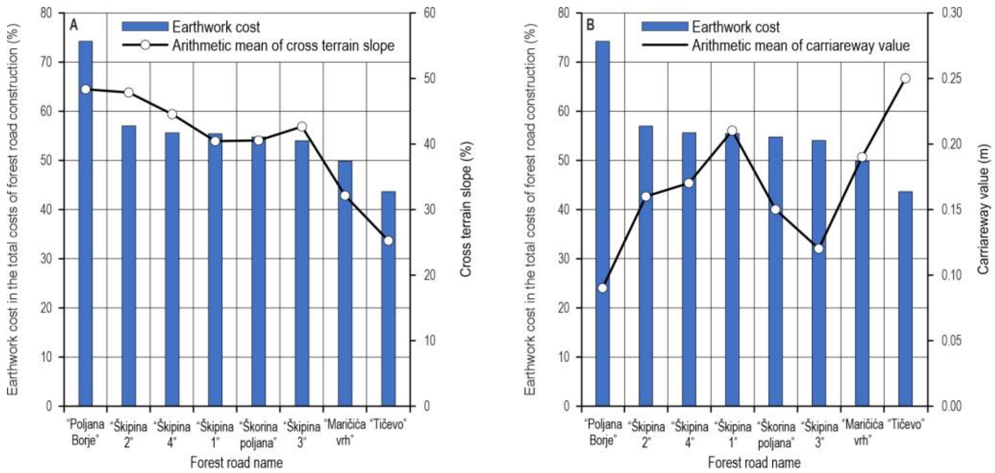

Figure 9. The influence of the cross terrain slope (**A**) and the carriageway value (**B**) on the share of earthwork costs in the total costs of the forest road construction.

As expected, the lowest share of earthwork cost (Figures 9A and 10) in relation to the total cost of construction was recorded on the forest road "Tičevo", where the lowest average cross terrain slope (25.24%) was observed, i.e., it had the lowest share of material of category A (the heaviest) (9.52%) during the field assessment of the construction material category (Table 6).

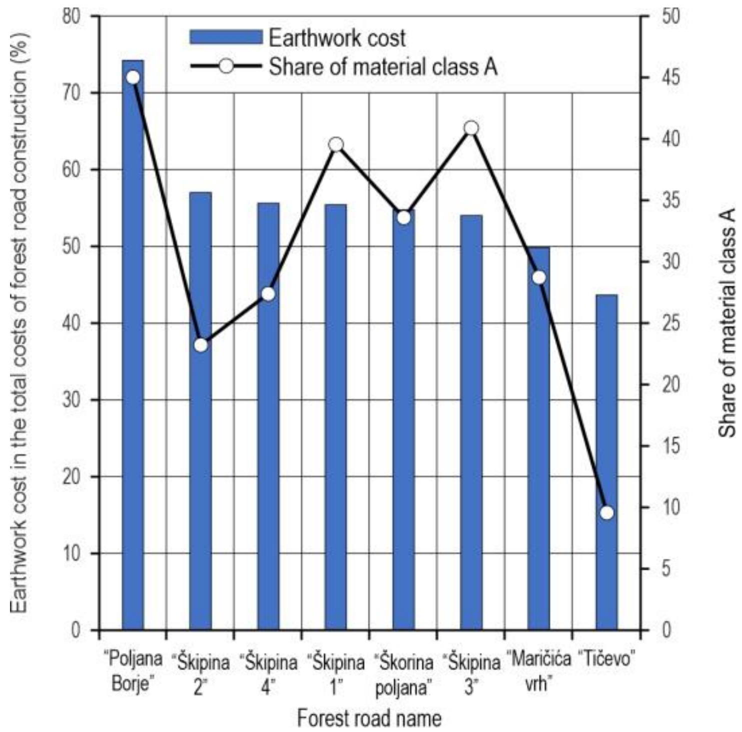

Figure 10. Influence of the share of material of category A on the share of earthwork cost in total cost of forest road construction.

Table 6. Number of cross section profiles per material category.

Material Category	"Poljana Borje"	"Škipina 2"	"Škipina 4"	"Škipina 1"	"Škorina Poljana"	"Škipina 3"	"Maričića Vrh"	"Tičevo"
B	89	106	114	81	89	117	119	57
A	73	32	43	53	45	80	48	6
B (%)	54.94	76.81	72.61	60.45	66.42	59.09	71.26	90.48
A (%)	45.06	23.19	27.39	39.55	33.58	40.91	28.74	9.52

The largest share of earthwork cost (Figures 9A and 10) in relation to the total cost of construction was recorded on the forest road "Poljana borje", where the largest average cross terrain slope (48.33%) was observed, i.e., it had the highest share of material of category A (the heaviest) (45.06%) during the field assessment of construction material category (Table 6).

4. Discussion

The phases of planning, designing and the construction of forest roads on steep terrain have always been challenging for the designers. Unless properly implemented, the construction of forest roads can cause serious damage to the forest ecosystem [27]. This was clearly confirmed by this research, where earthwork volumes per 1 m of road reached maximum values of 17.12 m^3 m′ for cut volume and 14.15 m^3 m′ for fill volume. For this reason, it is of the utmost importance to make sure that each phase in establishing an optimal primary forest road network is completed in a timely way and satisfactorily [4]. In other words, although a moderate correlation was established between the cross terrain slope and occurrence of cut volume, i.e., a weak correlation between the cross terrain slope and occurrence of fill volume, it is indisputable that with the increase in the cross terrain slope, the earthwork volume also increases (Figures 4 and 5). It is therefore essential to take into account the cross terrain slope during the planning phase of forest roads, and to avoid as much as possible steep slopes, in order to minimize the earthwork volumes and hence the adverse impact of the forest road on the environment. Furthermore, by establishing a strong correlation between the carriageway value and occurrence of earthwork volume on the forest road route, we get the confirmation that each mistake in any phase of establishing an optimal primary forest road network will be reflected in its non-harmonious horizontal or vertical development, which will surely mean an increase in carriageway value, i.e., an increase in earthwork volume during the construction and consequently a higher adverse impact of the forest road on the environment. The estimate of infrastructure construction costs, i.e., the assessment of earthworks in the construction of forest roads on steep terrain, depends on the effect of different factors, which is further complicated by the environmental restrictions reflected through changing topography, different types of soil on the forest road route and the changing share of rockiness, as confirmed by previous research [32,33].

This research took into consideration the following factors affecting the estimate of earthwork costs during forest road construction: cross terrain slope, carriageway value and share of different material categories; however, it should be noted that it is very difficult to find reliable data on any of the above mentioned factors without the direct field measurement of profiles [40]. Based on the available data on the three above specified influential factors, we could only make an assessment of the values of the cross terrain slope, where the values of the field measurements or assessments based on the accurateness of non-interpolated DTM with pixel size 15 × 15 m are presented in Figure 3. The assessment model based on non-interpolated DTM proved to be unreliable because it wrongly assessed the slope class in 84.65% profiles, while the assessment model based on interpolated DTM proved to be more accurate with an estimated accuracy in 68.52% cases. Further to the above, it can be concluded that no model, among the ones used, was accurate enough for assessing the slope class when designing forest roads on steep terrain, by which the results of [47] have been confirmed; they state that only digital terrain models of high accuracy can be applied in designing or assessing earthwork volumes during forest road construction. This is also in accordance with the results of [48], which state that the smallest information carrier (grid), with an area of 10 × 10 m, is satisfactory for practical use.

The analysis of the cross terrain slope obtained by reading cross-section profiles made on the basis of field data, i.e., by direct field measurement of profiles, unquestionably indicates that the increase in cross terrain slope and carriageway value result in the increase in the earthwork volume, which is in line with the results of Sokolović and Bajrić [40]. Taking into consideration the coefficients of determination, it can be seen that the impact of cross terrain slope on the occurrence of cut and fill volume on forest road route results in a moderate (R^2 = 0.3167) and weak (R^2 = 0.2076) correlation. On the other hand, a moderate and strong correlation was established between the carriageway value and occurrence of cut and fill volume; it was defined by the coefficient of determination (R^2 = 0.6841) and (R^2 = 0.5619), respectively.

Based on the results presented, it can be concluded that the carriageway value is the dominant factor affecting the earthwork volume during the construction of forest roads on steep terrain. As stated above, this value is under the highest influence of the designer, i.e., the carriageway value is the only value which the designer of the forest road can directly influence by fitting the level line into longitudinally terrain configuration. It should be emphasized that the highest data dispersion with the lowest coefficients of determination was observed for the highest slope class (slope class 4, cross terrain slope >76.01%) due to the fact that this class had a small number of samples/profiles, n = 23, which is only 1.99% of all analyzed profiles. Further research should focus on these extreme slopes so as to obtain a larger sample and a higher coefficient of determination. Unfortunately, this research failed to confirm the results of Potočnik [39], who outlines that with the increase in cross terrain, the carriageway value also increases; this is supported by the fact that the impact of the coefficient of determination of cross terrain slope on the occurrence of carriageway value in our sample was R^2 = 0.0206, which is a weak correlation according to the Chaddock scale [46].

The analyzed data further show that the average carriageway value of all analyzed profiles is −0.09 m, i.e., the carriageway value is lower than the ground level, which can be explained by the fact that the intent of the designer is always to provide forest road construction of maximum stability at a reasonable cost. In dealing with steep terrain, with the average value of a cross terrain slope of 41.35% and maximum recorded value of 91.83%, the idea of the designer was to minimize the cases of long embankment slopes, which, according to the research of Potočnik [39], require additional soil stabilization, causing an increase in the entire construction cost. The above is also confirmed by the average values of the analyzed profiles, amounting to 3.47 m^3 m′ for the cut volume, and 2.37 m^3 m′ for the average value of the earth material fill volume, i.e., the average value of the cut volume is 1.10 m^3 m′ higher than the fill volume, which clearly indicates that the main intent of the designer was to construct forest roads with maximum stability on the steep terrain of the study area.

Although, in terms of earthwork costs during the construction of forest roads, the ideal scenario is the one in which the carriageway value represents the minimum difference between the cut and fill volume per 1 m of forest road, and in our sample the carriageway value was 0.051 m (Figure 8), in order to provide maximum forest road stability, such a carriageway value cannot be expected and on steep terrain these values will always be somewhat lower. In our case, the difference between the optimal carriageway value, where the difference between the cut and fill volume would be the minimum (0.051 m), and the average actual carriageway value of all analyzed profiles (−0.09 m) is 0.0141 m, meaning that the actual carriageway value is 14 cm lower than the optimal one, but optimal only in terms of the difference between the cut and fill volume. It should also be emphasized that in 96.7% of all analyzed profiles, the carriageway value ranged between – 1 m and 1 m and only in 38 profiles were lower or higher carriageway values recorded. The greatest carriageway depth of –1.81 m was recorded on forest road "Maričića vrh" in the profile No. 45, while the greatest carriageway height of 1.79 m was recorded on forest road "Škipina 4" in the profile No. 45.

An interesting fact was noticed related to the share of earthwork cost in the total cost of forest road construction, which ranged from a maximum of 74.22% on forest road "Poljana Borje" to a minimum 43.63% recorded on forest road "Tičevo". The strongest correlation of the share of earthwork cost in the total construction cost was recorded when analyzing the average cross terrain slope, where the share of earthwork costs gradually decreased with the decrease in the average cross terrain slope (Figure 9A). Such relationship was not recorded between the share of the earthwork cost in the total cost of forest road construction and the average carriageway value (Figure 9B) and share of material of category A (the heaviest) (Figure 10). We would like to draw attention to the case of the forest road "Tičevo", where the lowest average cross terrain slope was recorded, as well as the lowest share of material of category A (Figures 9A and 10) and at the same time the highest average carriageway value. Therefore, it can be seen that the carriageway value is most highly affected by the designer, who has the greatest possibility to increase the carriageway value on moderate sections of the route with a lower share of material of the highest category in order to minimize the cut and hence the damage to the forest ecosystem.

5. Conclusions

Based on the presented results, the following conclusions can be drawn:

- Due to the direct impact of the earthwork volume on the total costs of forest road construction, which are very high, the optimization of earthworks should be the main focus of designers in each working phase that ends with developing the main forest road project and the construction of forest road. Based on experience and respecting the rules of the profession, the designer of a forest road can have a great impact on the carriageway value, and hence also the earthwork volume on a forest road route.

- It is improper and inaccurate to make an assessment of cross terrain slope values based on non-interpolated DTM and interpolated DTM with pixel size 15 × 15 m, because the obtained results are not accurate and reliable enough.
- Based on the coefficient of determination, it can be concluded that the impact of the cross terrain slope on the occurrence of cut and fill volume on the forest road route is moderate or weak, while the correlation between the carriageway value and the occurrence of cut and fill volume is determined as a moderate or strong correlation.
- The analyzed profiles involved a small number of profiles located on cross-section slopes greater than 67%; it is therefore necessary to undertake further research into earthwork occurrence on such terrain.
- The intent of providing maximum stability to forest roads on steep terrain inevitably causes a difference between the carriageway value, where the difference between the cut and fill volume is minimum, and the average actual carriageway value, in favor of the carriageway value, where the difference between the cut and fill volume is minimum.
- On moderate cross sections of the route with a lower share of material of the highest category, the designer has the greatest possibility to increase the carriageway value with the aim of minimizing the cut and hence also the damage to the forest ecosystem.

Author Contributions: Conceptualization, I.P.; Data curation, D.V.; Formal analysis, M.L.; Funding acquisition, T.P.; Investigation, A.Đ.; Methodology, I.P.; Project administration, I.P.; Resources, R.P.; Software, D.J.; Supervision, I.P. and R.P.; Validation, R.P., D.J., R.V. and A.Đ.; Visualization, R.V.; Writing—original draft, I.P. and M.L.; Writing—review and editing, R.P. and A.Đ. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Croatian Science Foundation under the project "Quantity and structure of fir and spruce biomass in changed climatic conditions" (UIP-2019-04-7766).

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to thank Faculty of Forestry and Wood Technology University of Zagreb for all the support during the research.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Heinimann, H.R. Forest road network and transportation engineering–state and perspectives. *Croat. J. For. Eng.* **2017**, *38*, 155–173.
2. Picchio, R.; Pignatti, G.; Marchi, E.; Latterini, F.; Benanchi, M.; Foderi, C.; Venanzi, R.; Verani, S. The application of two approaches using GIS technology implementation in forest road network planning in an Italian mountain setting. *Forests* **2018**, *9*, 277. [CrossRef]
3. Akay, A.E.; Serin, H.; Sessions, J.; Bilici, E.; Pak, M. Evaluating the effects of improving forest road standards on economic value of forest products. *Croat. J. For. Eng.* **2021**, *42*, 245–258. [CrossRef]
4. Pentek, T.; Pičman, D.; Nevečerel, H. Uspostava optimalne mreže šumskih cesta na terenu—smjernice unapređenja pojedine faze rada. *Glas. Za Šumske Pokuse* **2006**, *5*, 647–663.
5. Pentek, T.; Pičman, D.; Nevečerel, H. Environmental-ecological component of forest road planning and designing. In Proceedings of the International Scientific Conference: Forest Constructions and Ameliorations in Relation to the Natural Environment, Zvolen, Slovakia, 16–17 September 2004.
6. Kramer, B.W. Road construction and reconstruction. In *Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners*, 1st ed.; Oregon State University, College of Forestry, Forest Research Laboratory: Corvallis, OR, USA, 2001; pp. 24–42.
7. Anonymous. *Forest Road Engineering Guidebook*, 2nd ed.; Forest Practices Code of British Columbia Guidebook: Victoria, BC, Canada, 2002.
8. Ryan, T.; Phillips, H.; Ramsay, J.; Dempsey, J. *Forest Road Manual: Guidelines for the Design, Construction and Management of Forest Roads*, 1st ed.; COFORD: Dublin, Ireland, 2004; pp. 65–128.
9. Adams, P.W.; Storm, R. Roads and stream crossings. In *Oregon's Forest Protection Laws*, 2nd ed.; Oregon Forest Resources Institute: Portland, OR, USA, 2011; pp. 102–130.
10. Anonymous. *New Zealanad Forest Road Engineering Manual*, 1st ed.; NZ Forest Owners Association: Welington, New Zealand, 2012.

11. Marie, M.K.; Adam, W.; Zbigniew, B. Effects of forest roads on oak trees via cervid habitat use and browsing. *For. Ecol. Manag.* **2018**, *424*, 378–386. [CrossRef]
12. Berenji Tehrani, F.; Majnounian, B.; Abdi, E.; Amiri, G.Z. Impacts of forest road on plant species diversity in a Hyrcanian forest, Iran. *Croat. J. For. Eng.* **2015**, *36*, 63–71.
13. Çalişkan, E.; Karahalil, U. Evaluation of forest road network and determining timber extraction system using GIS: A case study in Anbardağ planning unit. Šumarski List 2017, 141, 163–171. *Šumarski List* **2017**, *141*, 163–171. [CrossRef]
14. Borowski, Z.; Bartoń, K.; Gil, W.; Wójcicki, A.; Pawlak, B. Factors affecting deer pressure on forest regeneration: The roles of forest roads, visibility and forage availability. *Pest Manag. Sci.* **2021**, *77*, 628–634. [CrossRef] [PubMed]
15. Picchio, R.; Tavankar, F.; Venanzi, R.; Lo Monaco, A.; Nikooy, M. Study of forest road effect on tree community and stand structure in three Italian and Iranian temperate forests. *Croat. J. For. Eng.* **2018**, *39*, 57–70.
16. Lacerte, R.; Leblond, M.; St-Laurent, M.H. End of the road: Short-term responses of a large mammal community to forest road decommissioning. *J. Nat. Conserv.* **2022**, *69*, 126256. [CrossRef]
17. Fu, B.; Newham, L.T.; Ramos-Scharrón, C.E. A review of surface erosion and sediment delivery models for unsealed roads. *Environ. Model. Softw.* **2010**, *25*, 1–14. [CrossRef]
18. Grace, J.M., III. Predicting forest road surface erosion and storm runoff from high-elevation sites. *Trans. ASABE* **2017**, *60*, 705–719. [CrossRef]
19. Deljouei, A.; Sadeghi, S.M.M.; Abdi, E.; Bernhardt-Römermann, M.; Pascoe, E.L.; Marcantonio, M. The impact of road disturbance on vegetation and soil properties in a beech stand, Hyrcanian forest. *Eur. J. For. Res.* **2018**, *137*, 759–770. [CrossRef]
20. Jalali, A.M.; Naghdi, R.; Ghajar, I. Potential Evaluation of Forest Road Trench Failure in a Mountainous Forest, Northern Iran. *Croat. J. For. Eng.* **2022**, *43*, 169–184. [CrossRef]
21. Lane, P.N.; Sheridan, G.J. Impact of an unsealed forest road stream crossing: Water quality and sediment sources. *Hydrol. Process.* **2002**, *16*, 2599–2612. [CrossRef]
22. Robinson, C.; Duinker, P.N.; Beazley, K.F. A conceptual framework for understanding, assessing, and mitigating ecological effects of forest roads. *Environ. Rev.* **2010**, *18*, 61–86. [CrossRef]
23. Kleinschroth, F.; Healey, J.R. Impacts of logging roads on tropical forests. *Biotropica* **2017**, *49*, 620–635. [CrossRef]
24. Şakar, D.; Aydin, A.; Akay, A.E. Essential Issues Related to Construction Phases of Road Networks in Protected Areas: A Review. *Croat. J. For. Eng.* **2022**, *43*, 219–237. [CrossRef]
25. Mansouri, S.; Nasiri, M.; Modarres, A. Technical and Environmental Impacts of Coal Waste Used as a Soil Stabilizer in Construction Projects of Forest Roads. *Croat. J. For. Eng.* **2021**, *42*, 491–500. [CrossRef]
26. Solgi, A.; Naghdi, R.; Zenner, E.K.; Hemmati, V.; Behjou, F.K.; Masumian, A. Evaluating the effectiveness of mulching for reducing soil erosion in cut slope and fill slope of forest roads in Hyrcanian Forests. *Croat. J. For. Eng.* **2021**, *42*, 259–268. [CrossRef]
27. Caliskan, E. Environmental impacts of forest road construction on mountainous terrain. *Iran. J. Environ. Health Sci. Eng.* **2013**, *10*, 23. [CrossRef] [PubMed]
28. Epstein, R.; Weintraub, A.; Sessions, J.; Sessions, B.; Sapunar, P.; Nieto, E.; Bustamante, F.; Musante, H. PLANEX: A system to identify landing locations and access. In Proceedings of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium College of Forestry, Seattle, WA, USA, 10–12 December 2001.
29. Douglas, R.A. Road construction. In *Low-Volume Road Engineering: Design, Construction, and Maintenance*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2016; p. 256. [CrossRef]
30. Anonymous. Estimating road construction unit cost. In *Cost Control in Forest Harvesting and Road Construction*; FAO: Rome, Italy, 1992.
31. Anonymous. Potpora za Ulaganja u Infrastrukturu Vezano uz Razvoj, Modernizaciju i Prilagodbu Poljoprivrede i Šumarstva. Tipa Operacije 4.3.3. Ulaganje u Šumsku Infrastrukturu iz Programa Ruralnog Razvoja Republike Hrvatske za Razdoblje 2014–2020. In *Pravilnik o Provedbi Mjere M04 Ulaganja u Fizičku Imovinu Podmjere 4.3.*; Narodne novine broj 106/15. 65/17. 77/17. 84/18; Government of Croatia: Zagreb, Croatia, 2015.
32. Ghajar, I.; Najafi, A.; Karimimajd, A.M.; Boston, K.; Ali Torabi, S. A program for cost estimation of forest road construction using engineer's method. *For. Sci. Technol.* **2013**, *9*, 111–117. [CrossRef]
33. Bruce, J.C.; Han, H.S.; Akay, A.E.; Chung, W. ACCEL: Spreadsheet-based cost estimation for forest road construction. *West. J. Appl. For.* **2011**, *26*, 189–197. [CrossRef]
34. Pearce, J.K. Construction Engineering and Inspection. In *Forest Engineering Handbook*, 1st ed.; A Guide for Logging Planning and Forest Road Engineering; Bureau of Land Management: Washington, DC, USA; Oregon State Office: Corvallis, OR, USA; US Department of the Interior: Portland, OR, USA, 1961; pp. 209–220. [CrossRef]
35. Martinić, I. Ekonomski i Organizacijski Kriteriji za Oblikovanje Šumskih Radova. Ph.D. Thesis, Šumarski Fakultet Sveučilišta u Zagrebu, Zagreb, Croatia, 1995.
36. Sessions, J. Forest Road Construction. In *Forest Road Operations in the Tropics*, 1st ed.; Springer: Berlin/Heidelberg, Germany; New York, NY, USA, 2007; pp. 83–106. [CrossRef]
37. Stückelberger, J.A.; Heinimann, H.R.; Burlet, E.C. Modeling spatial variability in the life-cycle costs of low-volume forest roads. *Eur. J. For. Res.* **2006**, *125*, 377–390. [CrossRef]
38. Jeličić, V. Korištenje Dozera na Izgradnji Šumskih Puteva. Ph.D. Thesis, Šumarski Fakultet Univerziteta u Sarajevu, Sarajevo, Yugoslavia, 1975.

39. Potocnik, I. Depth of carriageway and cut slopes on forest roads. In Proceedings of the Zeszyty Naukowe Akademii Rolniczej w Krakowie, Sesja Naukowa, 91, Krakow, Poland, 15–18 June 2005.
40. Soković, D.; Bajrić, M. Volumen zemljanih radova pri izgradnji šumskih cesta na strmim terenima. *Nova Meh. Šumarstva: Časopis Za Teor. I Praksu Šumarskoga Inženjerstva* **2015**, *36*, 33–42.
41. Anonymous. *Opći Tehnički Uvjeti za Radove na Cestama*, 1st ed.; Book II—Zemljani radovi. odvodnja. potporni i obložni zidovi; Institut Građevinarstva Hrvatske: Zagreb, Croatia, 2001; p. 156.
42. Moeini, M. Applied algorithm hourly rate analysis of construction equipments. In Proceedings of the First International Conference of Project Management, Tehran, Iran, 27 June–1 July 2004.
43. Nevečerel, H. Dizajniranje Teorijskog Modela i Izrada Računalnog Programa za Projektiranje Šumskih Prometnica. Ph.D. Thesis, Šumarski Fakultet Sveučilišta u Zagrebu, Zagreb, Croatia, 9 December 2010.
44. Jeličić, V. *Šumske Ceste i Putevi*, 1st ed.; Samoupravna Interesna Zajednica Odgoja i Usmjerenog Obrazovanja Šumarstva i Drvne Industrije: Zagreb, Croatia, 1983; p. 193.
45. Anonymous. *Izmijenjena i Dopunjena Metodologija Izrade Registra Šumskih Cesta*; (DIR-01-2008-1705/01); Government of Croatia: Zagreb, Croatia, 2008.
46. Chaddock, R.E. *Principles and Methods of Statistics*, 1st ed.; Houghton Miffin Company: Boston, MA, USA; The Riverside Press: Cambridge, UK, 1925; pp. 248–303.
47. Akgul, M.; Yurtseven, H.; Gulci, S.; Akay, A.E. Evaluation of UAV-and GNSS-based DEMs for earthwork volume. *Arab. J. Sci. Eng.* **2018**, *43*, 1893–1909. [CrossRef]
48. Saarilahti, M. Modeling of the Wheel and Soil. In *Development of a Protocol for Coefficient Wood Harvesting on Sensitive Sites*; Soil interaction model, Apendinx Report no. 8; Ecowood: Oradea, Romania, 2022; pp. 1–37.