

Forest Road Design Based on Different Methods of Field Data Survey

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Abstract

In today's modern forestry, which is founded on sustainable management and development, it is essential to carry out the design phase of forest roads with quality, both for financial and environmental reasons. The basis for this is high-quality field data. This research tested available and potentially suitable methods for field surveys in the process of designing a forest road, including the classical survey method, GNSS and total station survey, as well as structure from motion and airborne lidar scanning survey. A total of 23 forest road designs were created through 3 design methods. Four important forest road parameters were tested: cut and fill volume, carriageway value and roadway width. No statistically significant difference was found for any of the tested parameters between the methods. Total station and ALS-based designs showed the lowest values of cut and fill volumes, 2.41 m³ and 2.54 m³ for the total station design, and 3.20 m³ and 2.47 m³ for the ALS design. Although some deviations were found between SfM designs based on different flight parameters, they were not significant. The results indicate the possibility of using all tested methods in forest areas with steep terrain, after a salvage logging has been performed. Also, by using three design methods and testing their results provides guidance how to test different measurement systems in the future when designing forest roads.

Keywords: photogrammetry, theodolite, total station, LiDAR, UAV, forest accuracy, forest road, design, earthworks

1. Introduction

A well-planned and designed road enables the fulfilment of all road tasks, such as: wood transportation (Sessions et al. 2015), access to forest for management and conservation (Sessions 2007), fire protection (Laschi et al. 2019) and recreation (Ryan et al. 2004). Forest roads, as a special ecosystem (Lugo and Gucinski 2000), influence and change the area in which they are located (Borga et al. 2005, Boston 2016, Kastridis 2020, Borowski et al. 2021). In addition, they directly affect the cost of forest operations (Akay and Sessions 2001, Chung et al. 2008). For these reasons, it is essential to carry out the planning and design phase of a forest road with high quality. The basis is to understand the morphometric parameters of the terrain (Dražić et al. 2023), forest management type (Lyons et al. 2022), climate zone (Motlagh 2024) and high-precision spatial data of the area of interest (Arıcak 2015).

According to Papa et al. (2017), two main survey methods are used for field survey of planned forest roads: classical and modern. Depending on the coun-

try or the method of data collection, the classical survey method uses a combination of different survey equipment: meridian clinometer, compass, theodolite, level and a measuring tape (Keller and Sherar 2003, Enache 2009, Douglas 2016, Papa et al. 2017), while modern survey method uses total station or GNSS (Global Navigation Satellite System) device (Papa et al. 2017). Although computer-aided design based on DTM (Digital Terrain Model) (for example, created based on LiDAR data) has been known to the profession for a long time (Pereira and Janssen 1999, Coulter et al. 2001), it is only with the increased availability of photogrammetric and lidar technology (primarily due to Unmanned Aerial Vehicles (UAV)) that these systems are slowly entering the forest road design process. Kınalı and Çalışkan (2022) compared forest road designs based on total station and SfM (Structure from Motion) survey from different flight heights (50, 75 and 100 m). The SfM flight height of 50 m design resulted in the smallest difference compared to the total station, with 0.27% less cut volume and 1.08% more fill volume. Taş et al. (2023) compared designs based

on SfM, GNSS-GPS and total station data and found greater differences between the quantities of earthwork compared to Kınalı and Çalışkan (2022). Compared to the total station device, the SfM method resulted in 14.8% less cut and 9.03% less fill. In comparison to the GNSS device, it achieved 29.1% more cut and 17% less fill. Based on the GNSS device, compared to the total station, the project achieved 34% less cut volume and 9% more fill volume. Matinnia et al. (2018) conclude that lidar systems can be used in forest road design after determining an average cut and fill difference of 2.39 and 3.18 m³ for road 1, and 2.98 and 5.60 m³ for road 2, compared to a total station design. The authors confirm the claims of Contreras et al. (2012), who emphasise canopy cover density and terrain ruggedness as factors that can influence the accuracy of earthwork quantity calculations. While SfM and lidar surveys are used and accepted as an accurate measurement method for specific forest parameters (Açıl et al. 2023, García-Cimarras et al. 2023, Manase et al. 2025, Spiers et al. 2025), their applicability has not been sufficiently investigated in the design of forest roads, based on available literature. For this reason, in this research, SfM and lidar survey will be called the experimental survey method.

This research tested different field survey methods required for forest road design on a large number of road-cross sections. The tested parameters of the designed forest road were selected based on economic

and environmental considerations: earthwork volumes (fill and cut), carriageway value and roadway (right of way) width. Earthwork amount directly affects forest road construction costs (Stückelberger et al. 2006) and can have significant environmental impacts, especially on soil erosion (Hacisalihoğlu et al. 2019) and nearby trees (Caliskan 2013). The carriageway value, defined as the difference between the road surface (wearing course) height and the ground height, is directly related to the cut and fill amount (Sokolović et al. 2015, Papa et al. 2023), and thus can have a significant economic and environmental impact. Although the width of the road, or the right of way, does not necessarily have much effect on the cost price, Zou et al. (2020) found that the width and shape of the road can lead to significant ecological changes, such as affecting the amount of biomass and soil pH.

2. Materials and Methods

2.1 Study Area and Data Collection

The study area is located in the Republic of Croatia in a forest area managed by the company Croatian Forests Ltd. (management unit Miletka, section 44c and section 44d). Due to a bark-beetle outbreak (*Ips typographus*) in 2016 and 2017, salvage logging was performed. After the salvage logging, the surface was partially covered with biomass (branches and plant

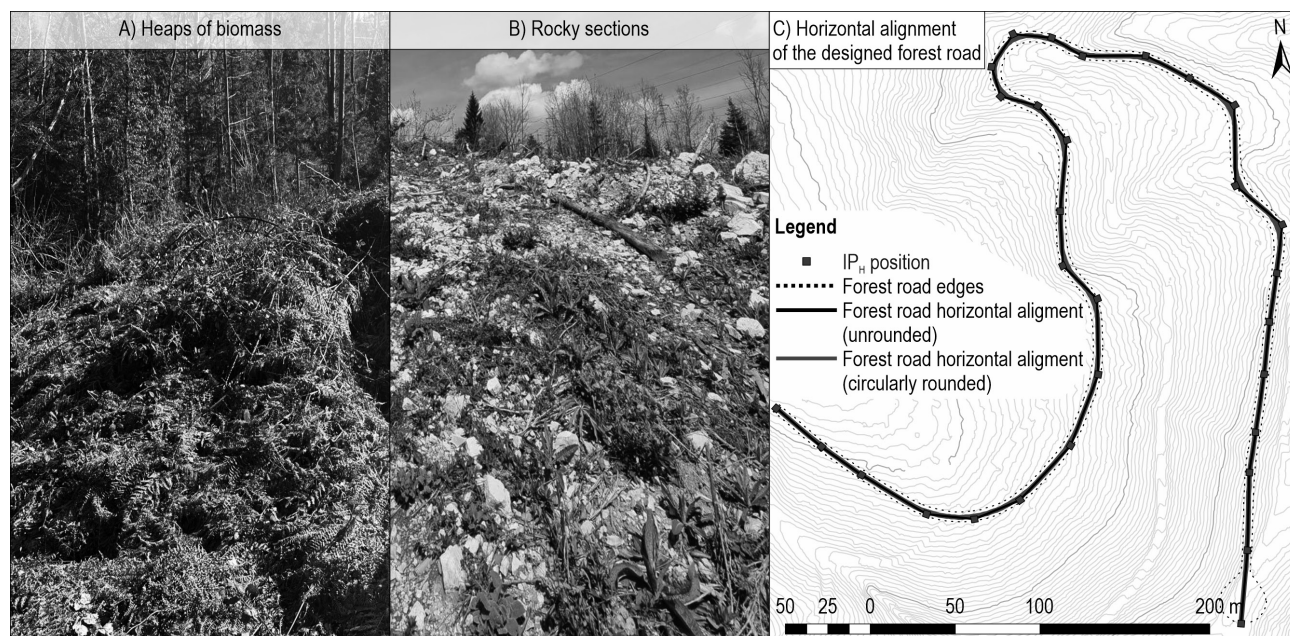


Fig. 1 A and B show field conditions during the research. Contour interval of 1 m

parts) stacked in piles (Fig. 1A). The average terrain slope for the research area is 32.00%, placing it in the category of moderately steep terrain (Mellgren 1980). This terrain slope presents a challenge during road design and construction, as confirmed by Jeličić's (1975) terrain classification, which states that it is necessary to design and construct embankment benches for slopes between 20% and 50%. In addition to the slope, the terrain where the research was conducted is characterised by pronounced microrelief and terrain obstacles in the form of rocks (Fig. 1B).

For the research purposes, two (out of four) phases of the forest road optimal network establishment were carried out: the road planning and design (Ryan et al. 2004, Pentek et al. 2014). Several versions of the zero line were placed on a 1:25,000 scale map, and the best one was selected and transferred to the field. The maximum longitudinal slope used was 12%. Based on the selected zero line, the horizontal alignment of the forest road was defined in the field by 30 horizontal intersection points (IP_H) (Fig. 1C).

3 different survey methods were used for the field survey (Table 1):

- ⇒ classical survey method (using theodolite, level, and geodetic rod)
- ⇒ modern survey method (total station and GNSS device)
- ⇒ experimental survey method (UAV equipped with RGB camera, Lidar data).

Classical (traditional) survey method, although in most cases replaced by modern survey method, is still in use in specific forest conditions (dense canopies of selected forests and regular forests under leaf-on condition or developed forest understory), where the use of a GNSS device or a total station is limited (Lee et al. 2023). As previous research has shown (Lovrinčević et al. 2025), a total station, which is an almost perfectly accurate instrument under optimal conditions, loses accuracy with frequent device movements. For that reason, a total station was not the reference method in this research. Field conditions for this research (salvage logging before data collection) allowed the GNSS

Table 1 Design cases based on survey method and selected parameters

Survey method	Used equipment	Important survey parameters		Abbreviation *	Additional explanation
Classical	Theodolite (Geomax ZIPP 02) Level (Sokkia C330)	Number of device relocations: 28 (theodolite) 28 (level)		FR _C	–
Modern	GNSS device (Stonex S900A)	The device used in RTK mode the Croatian Positioning System (CROPOS) correction base		FR _{GNSS}	–
	Total station (Stonex R35)	Number of device relocations: 28		FR _T	–
Experimental	UAV SfM (DJI Mavic 3 Enterprise with RTK correction)	Flight height	Terrain follow option	–	–
		60	No (UAV _{60NF})	FR _{60NF}	–
		70	No (UAV _{70NF})	FR _{70NF}	–
		70	Yes (UAV _{70F})	FR _{70F}	–
		70	Yes (UAV _{70MC})	FR _{70MC}	Manual classification of the point cloud performed. UAV _{70F} point cloud used
		90	Yes (UAV _{90F})	FR _{90F}	–
	Lidar data (airborne lidar scanning (ALS) data from the Croatian Geodetic Administration)	minimum horizontal accuracy ±0.2 m	minimum height accuracy ±0.1 m	FR _{ALS}	The entire territory of the Republic of Croatia was recorded by ALS. Recording requirements are described in the product specification (Anon. 2022). Minimum of 4 points per m ²

* For a design project based on different survey methods

device in RTK mode to be used as the reference method. The UAV survey (UAV SfM) was carried out at different flight altitudes and with the terrain follow option turned on or off. For the UAV SfM survey mission, conducted from a height of 70 meters with the terrain follow option enabled, automatic and manual classification of the point cloud, used for the creation of the digital terrain model (DTM), was carried out. Manual classification was done to remove (correct) parts of the terrain (DTM), which, due to the omission (caused by piles of biomass on the ground), were wrongly classified and included/excluded during the creation of the DTM. Lidar data tested in this research is the result of airborne lidar scanning (ALS) of the Republic of Croatia. Product specification (Anon. 2022) required a minimum of 4 points per m² for forest areas.

A detailed description of the data collection (survey) methodology and its spatial accuracy analysis is described in Lovrinčević et al. (2025).

2.2 Data Processing

Based on the collected data, a forest road engineering design project (In the following text, the term design was used) was created for each survey method using RoadEng software (v.10.0.664.0) (Fig. 2A). Horizontal and vertical alignment were identical for every survey method except for the classical survey method, due to a certain horizontal deviation (error), where the radii used for rounding of horizontal curves were adjusted so that the tangent length was the same as for other survey methods. Horizontal alignment consisted of straight sections and 28 circular curves. The value of the used radii (R) ranged between 16 m and 2400 m. The total road length was 860.9 m (8+60.90 hm). At the end of the road, a circular turning point was designed (10 m radius), as it is a road element that requires a large amount of earthwork. Vertical alignment was defined with 12 vertical intersection points (IP_v), that is, 10 vertical curves, rounded by parabolas whose parabolic rate (K) ranged from 4.47 to 637.05. Road grade ranged from 3% to 12%. Average road grade was 7.91%. The typical cross-section, with all its elements, is shown in Fig. 3. The whole project was in accordance with the current technical requirements (specifications) for forest roads in the Republic of Croatia (Šikić et al. 1989, Anon. 2024).

As UAV SfM and lidar survey can result in larger amount of data (higher spatial resolution) (Dong and Chen 2017, Carrera-Hernández et al. 2020) than a total station or a GNSS survey, and distance between cross-sections affects the accuracy of earthwork volume calculations (Aruga et al. 2005), design projects were also

made based on the extracted points of the UAV SfM and lidar data DTMs (Fig. 2B). Points were extracted at the locations of the GNSS survey. The Z values of the points were derived using the update feature Z function in ArcMap (v.10.8). The third method of testing the data involved extracted points, similar to the second method, but with corrected vertical alignment (Fig. 2C). Based on the positions of the vertical IP_s from the GNSS design, the horizontal and vertical offset of the IP_v from the nearest cross-section of interest was determined. For each method, corrected vertical IP_v s were then set based on the established offsets. Cross sections of interest were placed on horizontal positions of the beginning of the curve (BC), end of the curve (EC), middle of the curve (MC) and sections where the distance between the EC of the previous curve and the BC of the next curve was greater than 15 m.

In total, 23 forest road designs were created based on 3 different design methods:

- ⇒ **Case A:** forest road designs based on full data set, same horizontal and vertical alignment for all designs
- ⇒ **Case B:** forest road designs based on extracted points, same horizontal and vertical alignment for all designs
- ⇒ **Case C:** forest road designs based on extracted points, same horizontal alignment and corrected vertical alignment for each survey method.

After completing the design phase for each survey method, the following values were read, necessary for cost calculation, and the construction of the forest road (Swift 1988, Sokolović et al. 2015, Jaafari et al. 2021, Papa et al. 2023) (Fig. 3):

- ⇒ Earthwork volumes (fill and cut), m³
- ⇒ Carriageway value, m
- ⇒ Roadway (right of way) width, m

In MS Excel, a database was created. Based on differences between the GNSS device (reference method) and other survey methods, root-mean-square error (RMSE) was calculated for the tested road parameters using the formula:

$$RMSE_{v_d} = \sqrt{\frac{\sum v_d^2}{n}} \quad (1)$$

Where:

- v_d represents value difference
- n represents number of observations.

Further statistical analysis was conducted using Statistica (v.14.0.0.15.) software. The Kolmogorov-

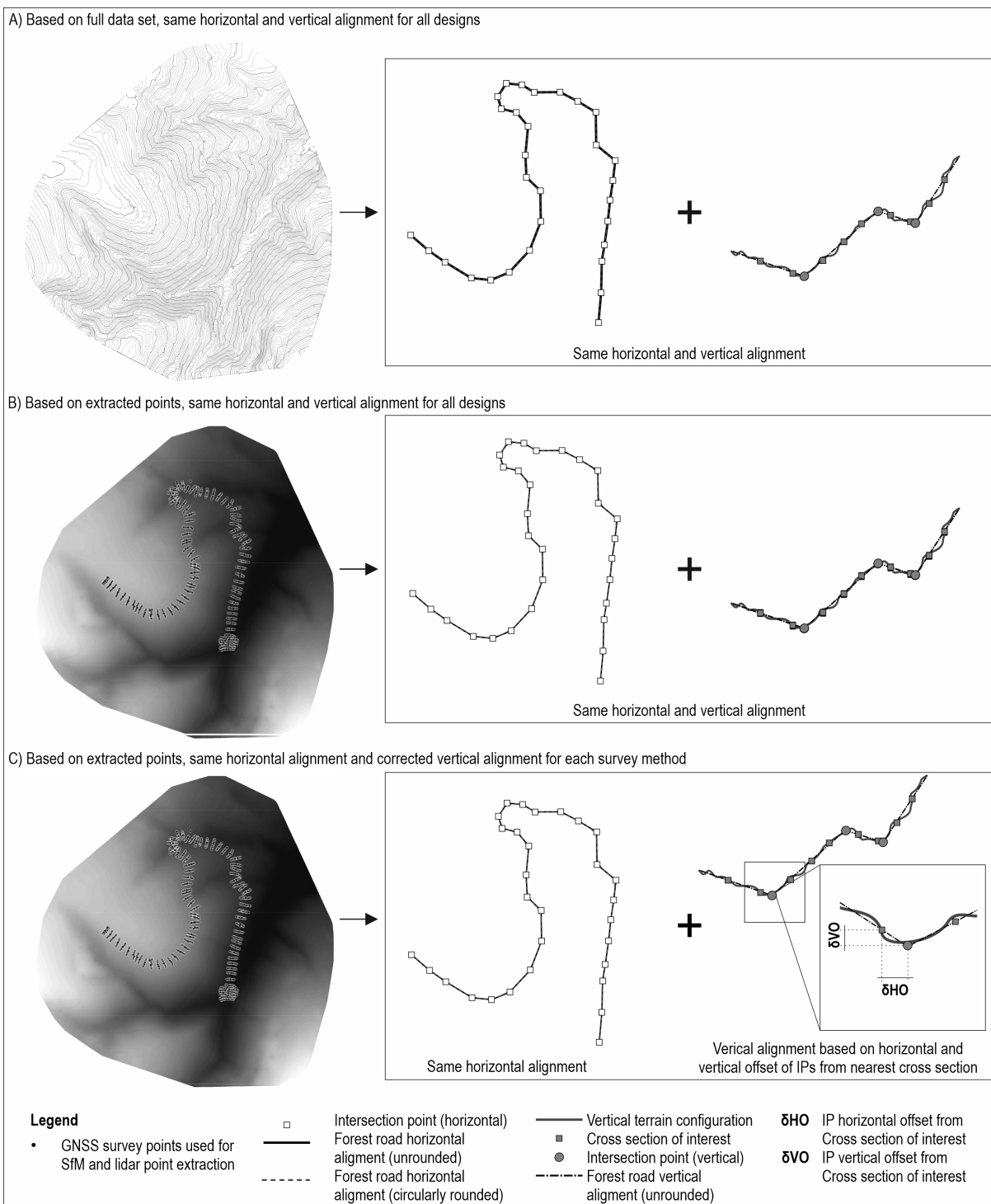


Fig. 2 Forest road design methods

Smirnov test was used to test data normality. Analysis of variance (ANOVA) was used to compare means between the survey methods, followed by a post hoc Tukey honest significant difference (HSD) test to identify which pairs of groups are statistically different.

3. Results

The results are presented based on the amount of field data used during the project design and on whether vertical alignment correction was performed.

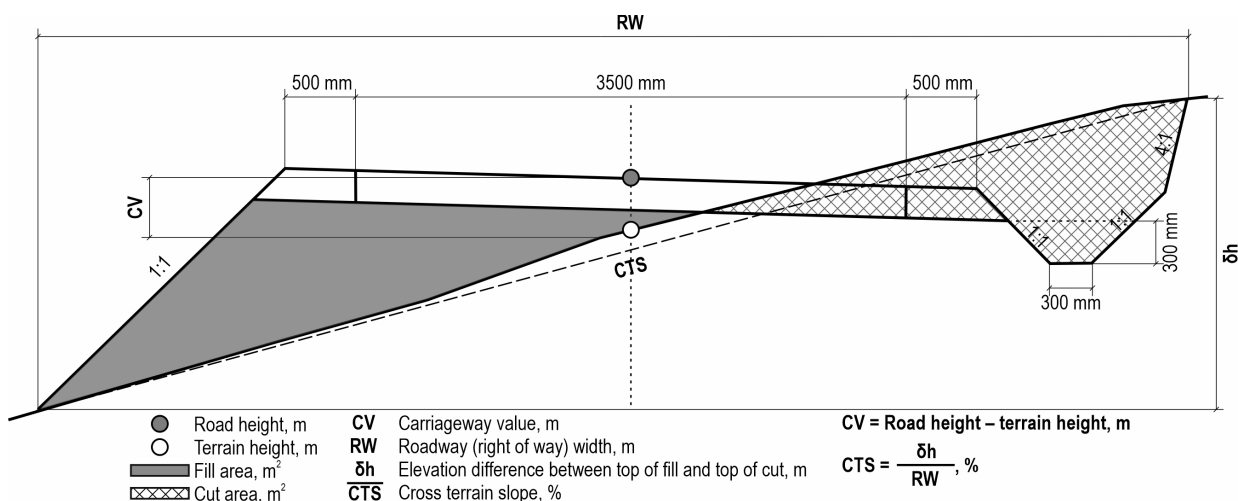


Fig. 3 Forest road cross-section with highlighted road parameters tested

3.1 Case A: Forest Road Designs Based on Full Data Set; Same Horizontal and Vertical Alignment

For this method of comparing survey methods, nine forest road designs were created, one for each survey method (Table 2). FR_{GNSS}, based on GNSS survey, resulted in 3789.34 m³ and 2380.09 m³ of calculated cut and fill volumes. FR_{60NF} achieved the most significant cut difference compared to FR_{GNSS}, +832.30 m³, while FR_T, FR_C and FR_{ALS} achieved the lowest differences, -317.52 m³, -280.49 m³ and -300.77 m³, respectively. Cut volume RMSE for the mentioned designs was 8.99 m³, 7.08 m³ and 6.90 m³, with underestimated cut volumes. Designs based on SfM survey overcalculated cut volumes, resulting in cut volume RMSE from 12.13 m³ (FR_{60NF}) to 9.13 m³ (FR_{70MC}). Considering only one cross-section, the most significant difference was recorded between cross-sections 13 and 14, in the FR_{60NF} design, in the amount of +34.39 m³. On the aforementioned cross-section, other SfM-based designs have made similar (large) errors, while the other methods recorded smaller errors: +12.31 m³ (FR_T), -1.11 m³ (FR_C), and +14.23 m³ (FR_{ALS}). The places where such larger errors were read are not related to the cut amount, since they were read at places of average cut amounts between cross sections (38.67 m³). In contrast to cut volumes, calculated fill volumes differed the least from the reference method for projects based on SfM survey, with a range from -378.69 m³ (FR_{60NF}) to -195.80 m³ (FR_{70MC}), with fill volume RMSE values ranging from 6.26 m³ to 5.00 m³, except FR_C, which recorded the lowest fill volume RMSE (4.55 m³). All SfM survey-based designs underestimated fill volumes. FR_{ALS} achieved the most significant differences in calculated fill volumes and

RMSE value, 629.26 m³ and 11.87 m³, respectively. FR_{ALS} also achieved the highest fill volume error between 2 cross sections in the amount of +51.27 m³ (between cross sections 30 and 31). In addition to FR_{ALS}, FR_T and FR_C also calculated more fill volume than FR_{GNSS}. FR_C achieved the closest accumulated volume value to the reference design (FR_{GNSS}), with a surplus of 1026.23 m³, which is 383.02 less than the FR_{GNSS} calculation. FR_{60NF} recorded +85.93% more accumulated volume than FR_{GNSS}.

Forest road designs based on survey methods that resulted in an underestimation of cut volume all had higher CV values than FR_{GNSS} (where a positive value indicates that the road surface is above ground level). In comparison, SfM-based designs had smaller values than FR_{GNSS}. FR_{ALS} design with the most calculated fill volume, had an average CV of 0.37 m, while FR_T had the highest CV RMSE value of 0.19 m. The highest error of this value was found in FR_{ALS} (+0.43 m), on cross-section 90.

The greatest average RW was observed in FR_T, and consequently, the clearing area too. FR_C had the highest RW RMSE (0.59 m), and FR_{70MC} had the lowest (0.26 m). SfM-based designs calculated a smaller clearing area compared to FR_{GNSS}.

As previous research using this data (Lovrinčević et al. 2025) indicated an increase in spatial data error, recorded by the classical survey method and total station, with moving away from the forest road route start (with station increase), cut and fill RMSE values were calculated for every section (every 100 m), and with station increase (Fig. 4). The smallest cut RMSE values (Fig. 4A) were achieved for the forest road section from 4+00.00 hm to 4+99.99 hm, regardless of the survey method. In this section of the designed forest road, the

Table 2 Descriptive statistics of parameters tested

	FR _{GNSS} (reference method)	FR _T	FR _C	FR _{60NF}	FR _{70NF}	FR _{70F}	FR _{70MC}	FR _{90F}	FR _{ALS}
Cut volume, m ³	3789.34	3471.82	3508.85	4621.64	4572.90	4422.73	4366.87	4424.03	3488.57
Cut difference to FR _{GNSS} , m ³	/	-317.52	-280.49	832.30	783.56	633.39	577.52	634.69	-300.77
Cut volume <i>RMSE</i> , m ³	/	8.99	7.08	12.13	11.67	9.86	9.13	10.07	6.90
Fill volume, m ³	2380.09	2878.74	2482.62	2001.40	2066.52	2160.16	2184.28	2145.40	3009.34
Fill difference to FR _{GNSS} , m ³	/	498.66	102.54	-378.69	-313.56	-219.93	-195.80	-234.69	629.26
Fill volume <i>RMSE</i> , m ³	/	9.83	4.55	6.26	5.90	5.24	5.00	5.29	11.87
Accumulated volume, m ³	1409.26	593.08	1026.23	2620.24	2506.37	2262.58	2182.58	2278.63	479.23
Accumulated volume difference to FR _{GNSS} , m ³	/	-816.18	-383.02	1210.99	1097.12	853.32	773.33	869.38	-930.03
Average carriageway value, m	0.24	0.34	0.30	0.12	0.13	0.17	0.18	0.17	0.37
Carriageway value <i>RMSE</i> , m	/	0.19	0.11	0.15	0.15	0.11	0.10	0.12	0.17
Average roadway width, m	9.46	9.58	9.38	9.38	9.40	9.40	9.41	9.37	9.57
Roadway width <i>RMSE</i> , m	/	0.33	0.59	0.33	0.32	0.29	0.26	0.34	0.33
Clearing area, m ³	7733.06	7860.54	7697.93	7659.68	7677.52	7681.17	7689.02	7664.84	7855.27
Clearing area difference to FR _{GNSS} , m ³	/	127.48	-35.14	-73.38	-55.54	-51.89	-44.04	-68.22	122.21

embankment-shaped cross-section dominated. For all designs, except for FR_C and FR_{ALS}, the highest cut *RMSE* was between station 1+00.00 hm and 1+99.99 hm. According to FR_{GNSS}, the total amount of cut volume for this section was 293.018 m³, while the designs with high cut *RMSE* in this section were calculated to be around 400 m³. Cut and fill *RMSE* values calculated for slope classes indicated an increase in *RMSE* values with increasing cross slope for FR_{ALS} (Fig. A1). The number of cross-sections in each cross-terrain slope class is shown in Table A1. FR_{ALS} recorded maximum fill volume *RMSE* for section 7 (16.48 m³). SfM-based designs fill *RMSE* fluctuated between 1.87 m³ and 8.78 m³. Cut volume *RMSE*, after the initial increase, was stable for all survey methods (Fig. 4B). Analogous case is with fill volume *RMSE*, except for FR_T, FR_C and FR_{ALS}, which had a growing trend with station increase.

ANOVA followed by Post hoc Tukey *HSD* (honestly significant difference) test found no statistically significant differences for tested parameters (Cut volume, Fill volume, CV and RW) between measuring methods (Fig. A2). Large data scatter was observed for cut, fill and CV values.

3.2 Case B: Forest Road Designs Based on Extracted Points; Same Horizontal and Vertical Alignment

Six forest road designs were created for this method of comparing survey methods, as FR_{GNSS}, FR_T and FR_C were already based on point data (Table 3). Using this data format, the calculated cut volumes decreased for

forest road designs based on SfM data, while for FR_{ALS}, the cut volume increased (now 6% more cut volume than FR_{GNSS}). For all methods for which a new design was created in this way, the *RMSE* value of the cut volume decreased. The most significant decrease in cut volume *RMSE* value was recorded for FR_{ALS} (now 3.97 m³), while the highest cut volume *RMSE* was recorded for FR_T (8.99 m³). The most significant cut volume error for a single cross-section was recorded in FR_C between cross-sections 97 and 98 (end of designed forest road) in the amount of -28.58 m³. The highest cut error recorded for the full data set design (FR_{60NF}, cross section 13–14, +34.39 m³) decreased to +11.31 m³ with this design method. Total fill volume decreased for SfM and ALS-based designs, -10.42% (FR_{70F}) and -6.40% (FR_{ALS}) compared to FR_{GNSS}. All mentioned designs underestimated the fill volume. FR_{ALS} recorded the most significant decrease in fill volume compared to its full data set design (-780.78 m³) and the lowest fill volume *RMSE* compared to FR_{GNSS} (2.30 m³). The highest error of fill volume was recorded between cross sections 76 and 77 in FR_T (+32.99 m³). FR_{60NF} resulted in the highest accumulated volume difference to GNSS (+73.98% more), while FR_C and FR_{ALS} recorded the lowest, -27.12% and +29.01% respectively.

Minimal changes were determined for the average CV of designs based on the survey methods for which the new project was created, except for FR_{ALS}, whose *RMSE* decreased to 0.08 m, the lowest *RMSE* of the tested methods. The most significant CV error on a single cross-section was determined for FR_{70NF} (cross-

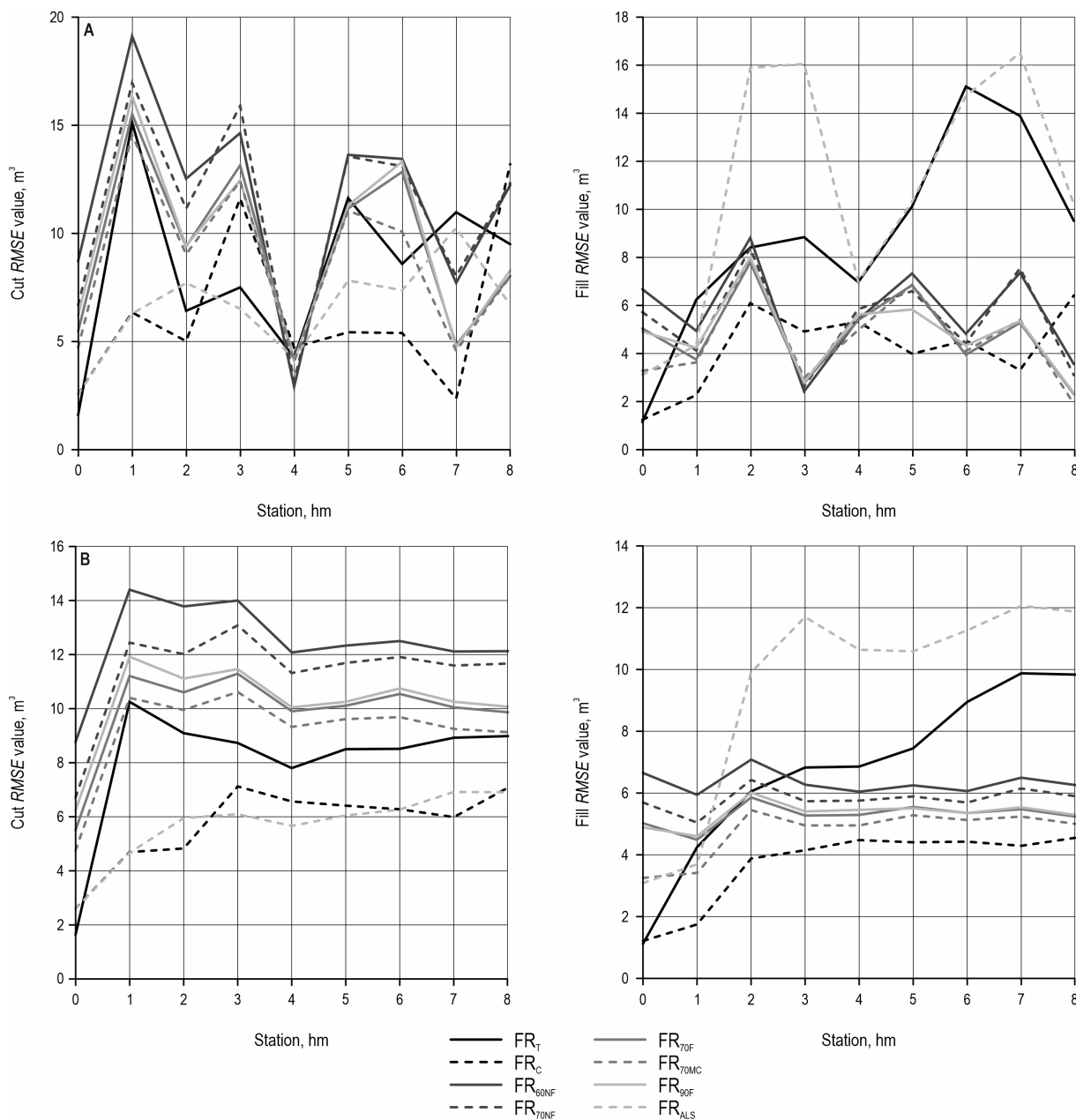


Fig. 4 RMSE values of cut and fill volumes based on full data sets designs of each method by station. **A)** represents the RMSE values for only one section of the designed forest road, for example, the station marked with 5 represents the section from station 5+00.00 hm to 5+99.99 hm. **B)** represents the RMSE values up to a certain station, for example, the station marked with 3 represents the RMSE values from 0+00.00 hm to 3+99.99 hm

section 45, -0.33 m). In the mentioned cross-section, the fill error was -6.25 m³, and the cut volume was 0 m³ (as in other designs). FR_T had the highest CV RMSE (0.19 m) and the most significant average RW (9.58 m). The average RW of FR_T resulted in the largest clearing area, 1.65 % larger than calculated in FR_{GNS}.

The cut value RMSE for road segments of all designs showed the lowest values on the section from

4+00.00 to 4+99.99 hm (Fig. 5A). SfM and ALS-based designs recorded smaller RMSE values across all sections compared to SfM and ALS designs based on full data sets. The highest cut RMSE values for the mentioned designs were recorded on the section from 1+00.00 hm to 1+99.99 hm. Fill volume RMSE of FR_T, except stations 4, 7 and 8, increased with moving away from the road start (Fig. 5B). Except for FR_T, after the

Table 3 Descriptive statistics of parameters tested

	FR _{GNSS}	FR _T	FR _C	FR _{60NF}	FR _{70NF}	FR _{70F}	FR _{70MC}	FR _{90F}	FR _{ALS}
Cut volume, m ³	3789.34	3471.82	3508.85	4398.357	4348.25	4191.96	4160.83	4218.47	4047.82
Cut difference to GNSS, m ³	/	-317.52	-280.49	609.02	558.91	402.62	371.49	429.13	258.48
Cut volume <i>RMSE</i> , m ³	/	8.99	7.08	8.21	7.64	5.79	5.27	6.19	3.97
Fill volume, m ³	2380.09	2878.74	2482.62	1946.56	2006.74	2132.78	2130.65	2100.31	2228.56
Fill difference to GNSS, m ³	/	498.66	102.54	-433.53	-373.34	-247.31	-249.43	-279.78	-151.53
Fill volume <i>RMSE</i> , m ³	/	9.83	4.55	5.85	5.29	3.86	3.80	4.11	2.30
Accumulated volume, m ³	1409.26	593.08	1027.05	2451.80	2341.51	2059.18	2030.18	2118.16	1819.26
Accumulated volume difference to GNSS, m ³	/	-816.18	-382.20	1042.55	932.25	649.92	620.92	708.90	410.00
Average carriageway value, m	0.24	0.34	0.30	0.12	0.14	0.17	0.18	0.17	0.20
Carriageway value <i>RMSE</i> , m	/	0.19	0.11	0.15	0.14	0.10	0.10	0.12	0.08
Average roadway width, m	9.46	9.58	9.38	9.36	9.39	9.41	9.41	9.37	9.43
Roadway width <i>RMSE</i> , m	/	0.33	0.59	0.33	0.29	0.19	0.18	0.28	0.12
Clearing area, m ³	7733.06	7860.54	7697.93	7631.42	7650.50	7681.58	7678.53	7660.11	7698.41
Clearing area difference to GNSS, m ³	/	127.48	-35.14	-101.64	-82.56	-51.48	-54.53	-72.95	-34.65

initial sharp increase in *RMSE* (cut and fill) values, no design showed a larger change (Fig. 5B). All designs showed lower *RMSE* cut values with cross-section slope increase, except FR_T, which did not show any trend or correlation (Fig. A3A). On the other hand, only FR_T showed an increasing fill volume *RMSE* value with cross-section increase, while other designs did not show any trend (Fig. A3B).

As with designs based on the full dataset, ANOVA showed no statistically significant difference between

the calculated parameters of designs based on the used survey methods (Fig. A4). Observed trends were the same as for designs based on full data sets.

3.3 Case C: Forest Road Designs Based on Extracted Points; Same Horizontal Alignment, Corrected Vertical Alignment

In total, eight new designs were created for this design method. As can be seen from Table 4, a reduction in cut difference to FR_{GNSS} was recorded for all

Table 4 Descriptive statistics of parameters tested

	FR _{GNSS}	FR _T	FR _C	FR _{60NF}	FR _{70NF}	FR _{70F}	FR _{70MC}	FR _{90F}	FR _{ALS}
Cut volume, m ³	3789.34	3886.12	3626.91	3798.24	3815.58	3815.29	3950.65	3881.37	3842.20
Cut difference to GNSS, m ³	/	96.78	-162.43	8.90	26.24	25.95	161.31	92.03	52.86
Cut volume <i>RMSE</i> , m ³	/	2.41	5.68	3.90	3.72	4.31	4.07	4.41	3.20
Fill volume, m ³	2380.09	2378.06	2372.57	2395.32	2418.03	2425.84	2279.55	2355.12	2391.46
Fill difference to GNSS, m ³	/	-2.02	-7.51	15.23	37.94	45.75	-100.53	-24.97	11.38
Fill volume <i>RMSE</i> , m ³	/	2.54	9.00	4.06	4.56	3.41	2.73	3.87	2.47
Accumulated volume, m ³	1409.26	1508.06	1254.34	1402.92	1397.56	1389.45	1671.10	1526.25	1450.74
Accumulated volume difference to GNSS, m ³	/	98.80	-154.92	-6.33	-11.70	-19.81	261.85	117.00	41.48
Average carriageway value, m	0.24	0.23	0.28	0.26	0.26	0.26	0.23	0.25	0.25
Carriageway value <i>RMSE</i> , m	/	0.03	0.09	0.10	0.11	0.09	0.08	0.10	0.08
Average roadway width, m	9.46	9.48	9.36	9.47	9.47	9.47	9.42	9.44	9.47
Roadway width <i>RMSE</i> , m	/	0.11	0.60	0.26	0.27	0.18	0.20	0.19	0.12
Clearing area, m ³	7733.06	7750.09	7676.39	7744.00	7749.53	7745.90	7695.92	7722.55	7735.38
Clearing area difference to GNSS, m ³	/	17.03	-56.67	10.94	16.47	12.84	-37.14	-10.51	2.32

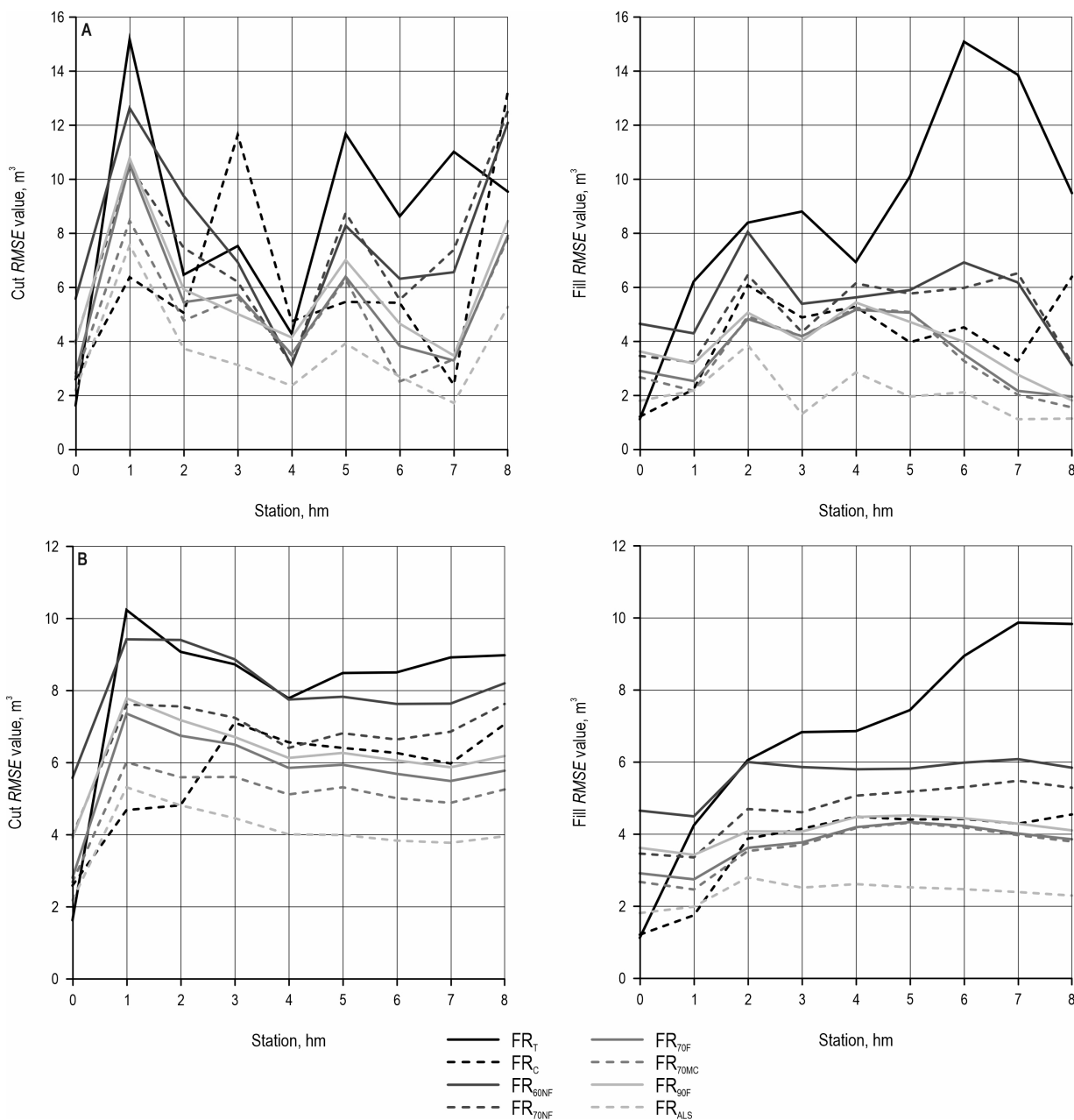


Fig. 5 *RMSE* values of cut and fill volumes based on extracted points designs of each method by station. **A)** represents the *RMSE* values for only one section of the designed forest road, for example, the station marked with 6 represents the section from station 6+00.00 hm to 6+99.99 hm. **B)** represents the *RMSE* values up to a certain station, for example, the station marked with 4 represents the *RMSE* values from 0+00.00 hm to 4+99.99 hm

created designs. Except for FR_C, all designs overestimated cut volume. The total amount of cut volume of FR_{60NF} differed the least from FR_{GNSS} (+0.02%). FR_{70MC} recorded the highest cut *RMSE* compared to other designs based on the SfM survey. Compared to FR_{70F}, cut volume of FR_{70MC} was 135.36 m³ higher. The lowest cut volume *RMSE* was recorded for FR_T (2.41 m³), and the highest for FR_C (5.68 m³), which also recorded the

highest cut error between cross sections (21.51 m³, cross sections 37–38). FR_{ALS} recorded the lowest difference in total fill volumes (+0.04%) and fill volume *RMSE* (2.47 m³) of all designs based on experimental survey methods. Between cross sections 86 and 87 in FR_C, the highest fill error was recorded (–17.26 m³). After this additional vertical alignment correction, all designs recorded lower accumulated volume differences

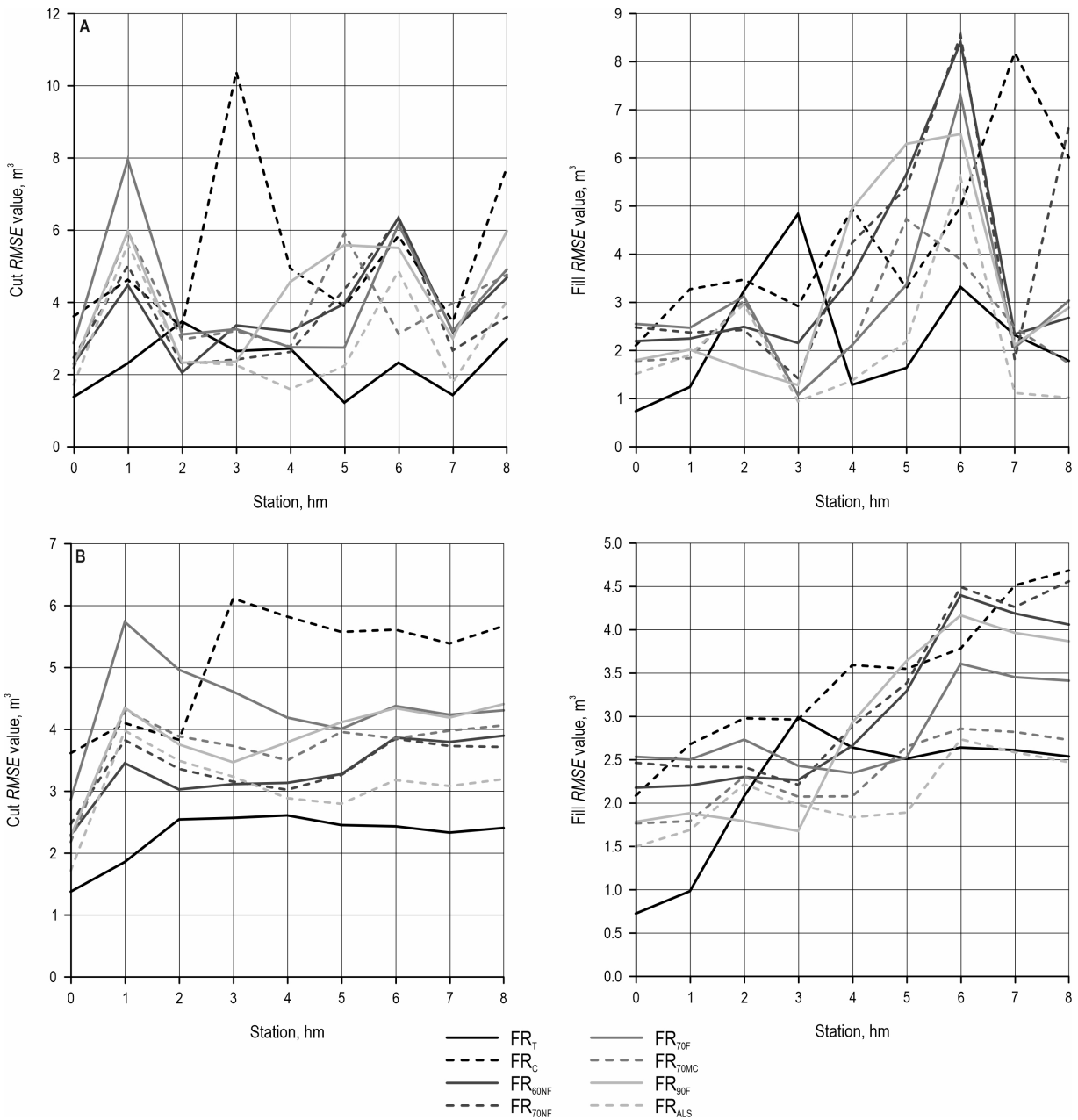


Fig. 6 *RMSE* values of cut and fill volumes based on extracted points and corrected vertical alignment designs of each method by station. **A)** represents the *RMSE* values for only one section of the designed forest road, for example, the station marked with 1 represents the section from station 1+00.00 hm to 1+99.99 hm. **B)** represents the *RMSE* values up to a certain station, for example, the station marked with 7 represents the *RMSE* values from 0+00.00 hm to 7+99.99 hm

compared to FR_{GNSS} ; FR_{60NF} recorded the lowest (-0.05%) and FR_{70MC} the highest (+18.58%).

FR_T recorded the lowest CV *RMSE*, and also the most significant change in its value compared to previous design methods. The highest error of CV was recorded in FR_{70NF} (cross section 73, CV error = +0.43 m). In the mentioned cross-section, the cut error was -1.81 m³, and the fill error was +1.83 m³. Except for

FR_{70MC} designs based on experimental survey methods resulted in higher average CV values.

FR_C designed by this method recorded the highest RW *RMSE* of all designs, regardless of the design or survey method (0.60 m).

Designs based on SfM and ALS achieved larger jumps in cut volume *RMSE* values at the same station (section), while this is not the case for those based on

the classical and total station survey method (Fig. 6A). Of all designs, FR_C achieved the highest cut $RMSE$ for section 3 (10.38 m^3). Section 1 (from 1+00.00 hm to 1+99.99 hm), section 6 and section 8 were sections where most designs recorded high cut $RMSE$ values. Only in section 8, a higher amount of cut volume was recorded (718.39 m^3). Most designs recorded the highest fill volume $RMSE$ in section 7. In section 7, a higher amount of cut and fill volume was calculated: 605.83 m^3 for cut and 462.92 m^3 for fill, respectively. Like in designs made with previously used design methods, cut volume $RMSE$ was stable after an initial jump in section 1 (Figure 6B).

In contrast to the cut volume $RMSE$, the fill volume $RMSE$ showed an increasing trend with moving away from the beginning of the forest road. This trend was most pronounced for FR_C . Analysing $RMSE$ values based on cross-section slope classes, no clear trend can be seen for either cut or fill $RMSE$ for any design (Fig. A5).

Finally, like with other design methods, ANOVA showed no statistically significant difference between the calculated parameters of designs based on the used survey methods (Fig. A6).

4. Discussion

As many countries still have low forest road density (Hodić and Jurušić 2011, Bilici and Akay 2021, Grajewski 2022, Lyons et al. 2023), and since the classical and modern method of field survey in forest road design is time and human-intensive, it is necessary to find an accurate and fast field survey method. In this article, all available and potentially suitable survey methods for field survey in the process of designing a forest road were tested. Nine different field surveys by five survey methods/devices were conducted. Collected field data were tested with three different design methods as experimental methods (SfM and ALS) were much bigger data sets (with higher spatial resolution (Dong and Chen 2017, Carrera-Hernández et al. 2020,)) and because, due to minor differences in the overall horizontal length of the designs, an error could have been caused by misaligned vertical alignment. In total, 23 forest road designs were created.

Case A – Forest road designs based on full data set; same horizontal and vertical alignment

Even though ANOVA showed no statistically significant difference for cut and fill volumes of forest road designs based on the full data set with the same horizontal and vertical alignment, between FR_{GNSS} and other methods (Fig. A2), high cut and fill volume

$RMSEs$ were recorded (Table 2). This can be explained by a large scatter of data. SfM designs overestimated cut volumes and underestimated fill volumes compared to FR_{GNSS} . The reason for this can be the fact that Z coordinate values of terrain obtained from SfM survey are constantly higher (with few exceptions), as shown in Lovrinčević et al. (2025). On the contrary, FR_{ALS} design underestimated cut volumes and overestimated fill volumes. In the mentioned research, ALS data had constantly lower Z coordinate values. SfM and ALS design results obtained from this design method are not in accordance with similar results of other authors (Matinnia et al. 2018, Kınalı and Çalışkan 2022, Taş et al. 2023), where differences in earthwork volumes were smaller when compared to designs based on total station or GNSS survey. It must be noted that the mentioned research used different design methodologies (horizontal and vertical alignment of the designed forest roads were not exactly the same between the survey methods), and that more field survey points were collected with GNSS and a total station. Analysis of the cut and fill volumes $RMSE$ in relation to slope class revealed an increase in the $RMSE$ of cut and fill values with increasing slope for FR_{ALS} , and $RMSE$ of fill values for FR_T (Fig. A1). Although this finding may be significant, there is an insufficient amount of data to draw firm conclusions (Table A1), and this trend was lost with designs created with other design methods. It would be essential to explore this in future research, as previous studies (Su and Bork 2006, Tinkham et al. 2012) have shown an increase in spatial inaccuracy of lidar scanning with increasing terrain slope. No clear relations between the total cut or fill amount between cross sections and the cut or fill error between them were found.

Case B – Forest road designs based on extracted points; same horizontal and vertical alignment

Error reduction of the parameters tested after creating new designs based on extracted points, with same horizontal and vertical alignment, points out that part of the error of the designs created with first design method is caused by the higher spatial resolution of field data (DTMs based on the SfM and ALS survey), and not only by the error of the mentioned measurement equipment/methods. The fact that SfM designs, again, overestimated cut volumes and underestimated fill volumes compared to FR_{GNSS} , confirms that higher Z values of SfM terrain points are the reason for a part of recorded errors, while lower Z values are the reason for fill volume overestimation and cut volume underestimation in FR_{ALS} . SfM recorded higher Z coordinate $RMSE$ values in section 4 (Lovrinčević et al. 2025), but that did not affect the results of tested designs. Even

though the previously mentioned research showed that the spatial error of the classical survey method and the total station is increasing with station increase, it did not affect the cut or fill *RMSE* of the mentioned survey methods, with the exception of fill values from FR_T .

Case C – Forest road designs based on extracted points; same horizontal alignment, corrected vertical alignment

Although the CV values were not statistically significantly different between the survey methods, for all design methods, only after creating projects with vertical alignment correction, the average CV values were approximately equal to the average CV value of FR_{GNSS} . This can explain the reduction in cut and fill volume error. Higher SfM design cut volume *RMSE* values on section 1 (Fig. 6A) can be explained by biomass recorded on the ground. As can be seen from Fig. 6B, the fill volume *RMSE* had an increasing tendency with station increase. The seemingly increasing trend in the fill volume *RMSE* of the SfM design is due to high values in section 6. A higher amount of fill volume was the reason for the high *RMSE* value. Errors were caused by Z coordinate error of SfM surveys (except for DTM based on manual classification) that was up to -0.50 m. The FR_T increase in fill volume *RMSE* with station increase was eliminated using this design method. As in other design methods, no clear connection was found between the earthwork error and the slope or the amount of cut/fill. Recorded horizontal offset of classical survey method and total station (Lovrinčević et al. 2025), did not affect the results of designs based on their field data.

The research confirmed the claim by Pereira and Janssen (1999) that a DTM created from lidar data with an average density of 4 points per m^2 is sufficient for the design of forest roads. Even though the earthwork errors recorded in SfM were greater than those in the research by Kınalı and Çalıřkan (2022) and Tař et al. (2023), we agree that SfM can be used in forest road design in areas like the one tested.

No significant differences were found for RW between the survey methods used, regardless of the design method.

5. Conclusions

Based on the research conducted, the following conclusions can be drawn:

- ⇒ testing of different measurement systems used for forest road design should be conducted at multiple levels, considering both spatial resolution and the design of the forest road

- ⇒ survey methods used so far (a classical survey method (theodolite, level) and a total station) are accurate enough for designing 1 km long forest roads, although they lose spatial accuracy with an increased number of device movements (Lovrinčević et al. 2025). Horizontal offset does not affect the design phase, but can potentially affect construction

- ⇒ in field conditions like those encountered during this research, the SfM survey provides sufficiently accurate field data for forest road design. Flight altitude and terrain follow function, which affected spatial accuracy (Table A2), did not have a significant impact on the results obtained. Also, the manual classification of the point cloud that was carried out for creating the DTM for the FR_{70MC} did not significantly affect the accuracy of the design

- ⇒ ALS provides accurate field data for designing forest roads in tested terrain conditions

- ⇒ future research on the application of SfM survey should be conducted in different relief areas and outside the vegetation period (leaf-off condition), as a closed canopy prevents obtaining a realistic representation of the terrain

- ⇒ future research on lidar systems needs to be conducted in different relief areas and both during and outside the vegetation season

- ⇒ it is necessary to encourage the use of systems such as SfM and lidar scanning as they provide higher spatial resolution data and allow larger area survey, which ultimately enables and empowers additional analyses that can be useful in forest road designs, such as watershed analysis. The result of such a design can be a combination of environmental protection and human needs.

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Appendix A

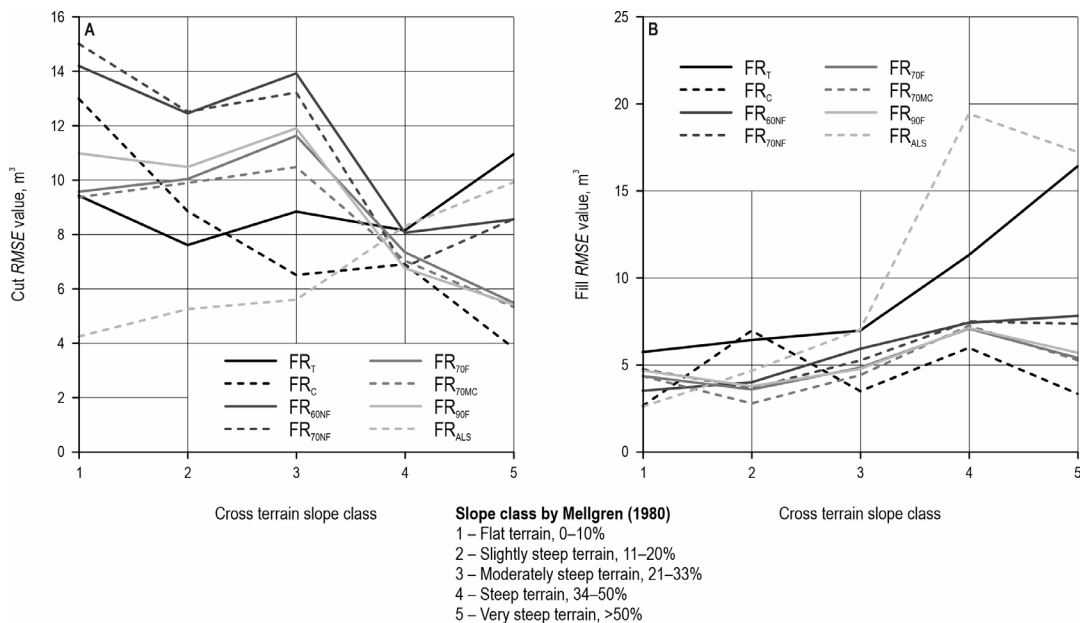


Fig. A1 Cut (A) and Fill (B) *RMSE* values by cross terrain slope classes. Forest road designs based on full data set; same horizontal and vertical alignment

Table A1 Number of cross sections by cross terrain slope classes

Slope class	Mellgren (1980)	Number of cross sections in class
1	Flat terrain, 0–10%	5
2	Slightly steep terrain, 11–20%	13
3	Moderately steep terrain, 21–33%	47
4	Steep terrain, 34–50%	17
5	Very steep terrain, >50%	16

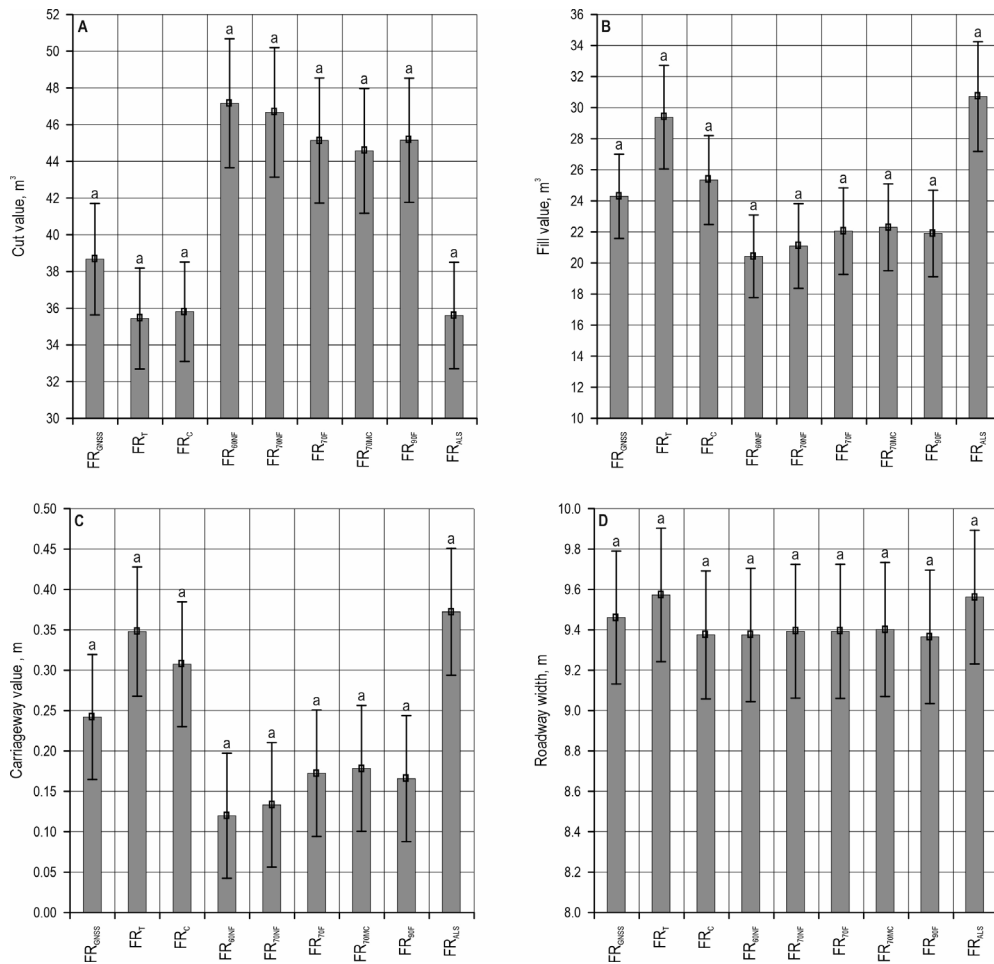


Fig. A2 Difference in tested parameters by measuring methods projects based on full data sets. Data are presented as mean \pm SE (standard error). A) Cut volume, B) Fill volume, C) Carriageway value and D) Roadway width. Letters denote statistical differences between measuring methods (Tukey HSD), respectively, at $p < 0.05$

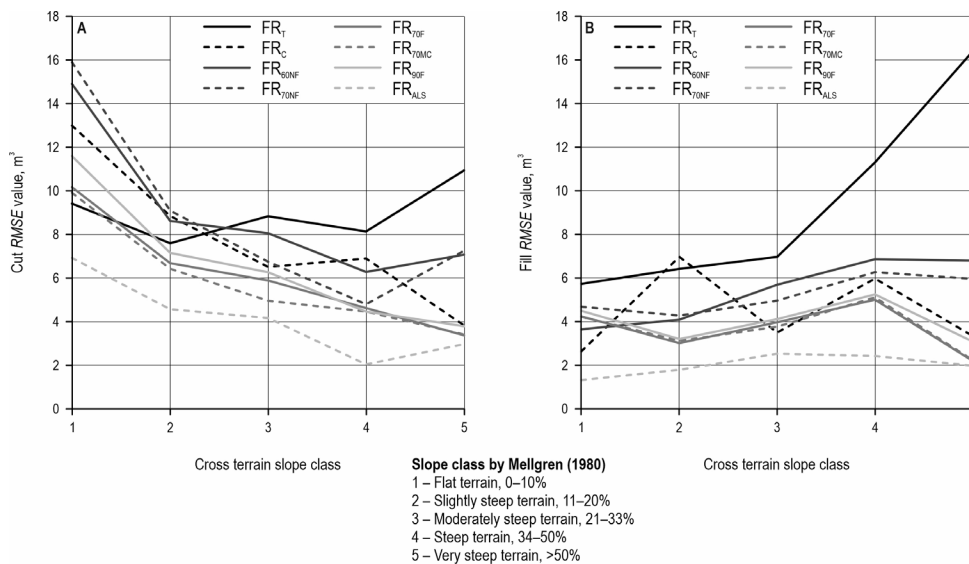


Fig. A3 Cut (A) and Fill (B) RMSE values by cross terrain slope classes. Forest road designs based on extracted points; same horizontal and vertical alignment

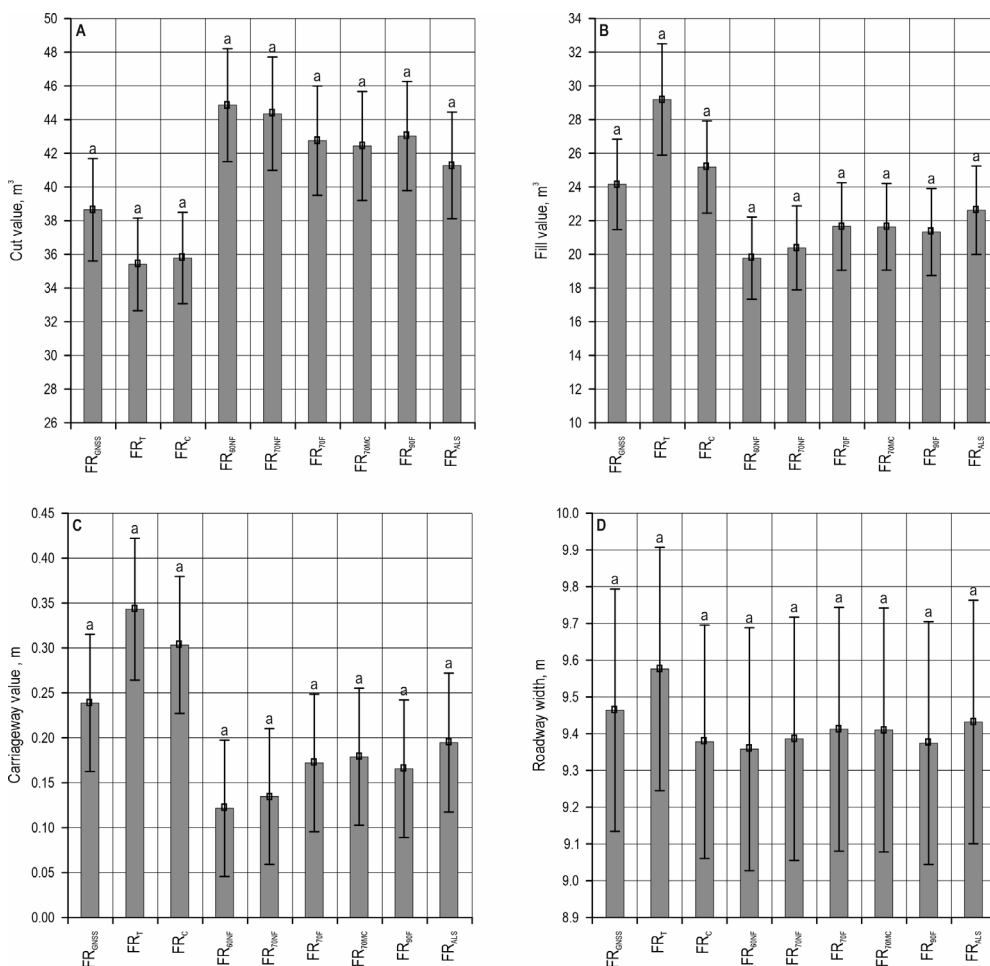


Fig. A4 Difference in tested parameters by measuring methods designs based on extracted points. Data are presented as *mean* ± *SE* (standard error). A) Cut volume, B) Fill volume, C) Carriageway value and D) Roadway width. Letters denote statistical differences between measuring methods (Tukey *HSD*), respectively, at $p < 0.05$

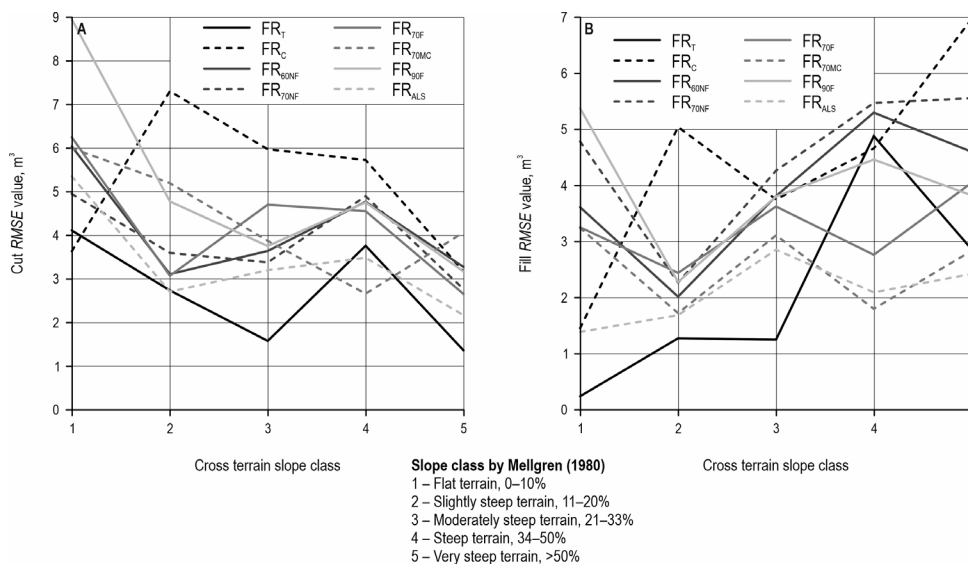


Fig. A5 Cut (A) and Fill (B) *RMSE* values by cross terrain slope classes. Forest road designs based on extracted points; same horizontal alignment, corrected vertical alignment

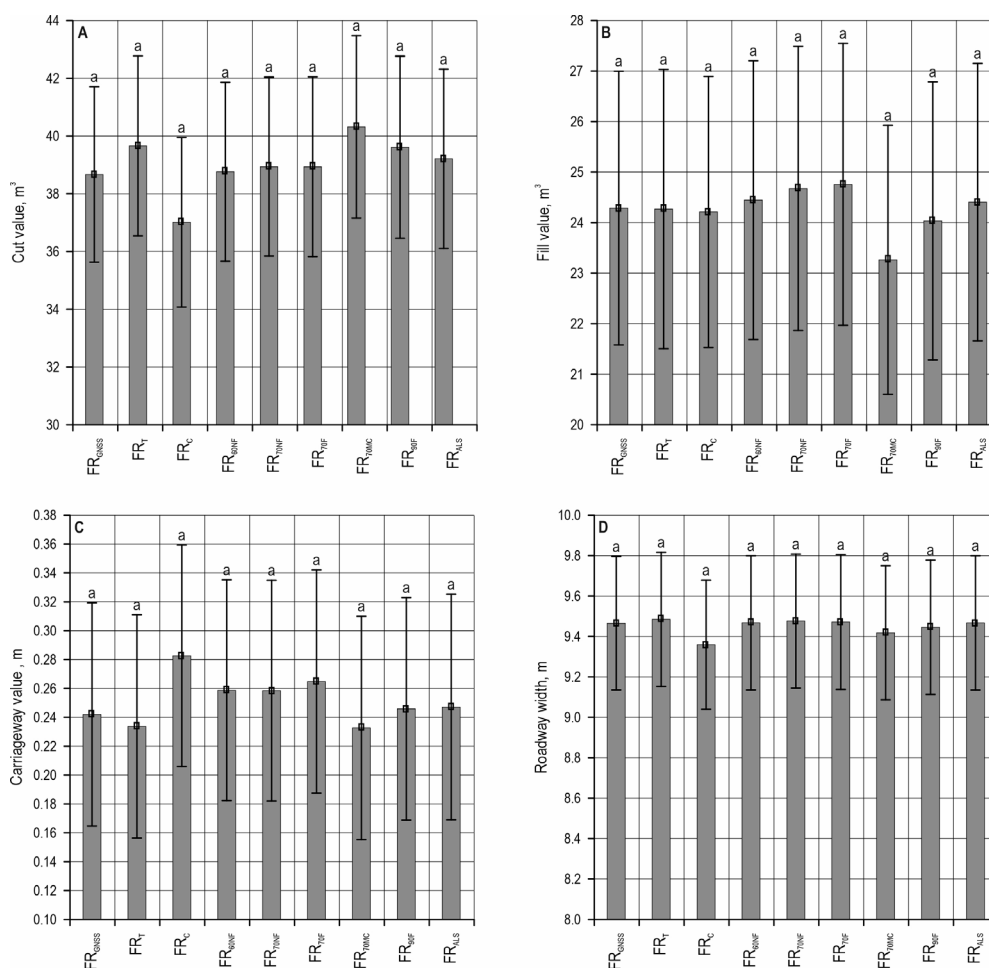


Fig. A6 Difference in tested parameters by measuring methods based on extracted points, same horizontal alignment, corrected vertical alignment. Data are presented as *mean* ± *SE* (standard error). A) Cut volume, B) Fill volume, C) Carriageway value and D) Roadway width. Letters denote statistical differences between measuring methods (Tukey *HSD*), respectively, at $p < 0.05$

Table A2 Spatial accuracy (coordinates *RMSE*) of tested field data by survey methods (Lovrinčević et al. 2025)

Coordinate	DTM _C , m	DTM _t , m	DTM _{60NF} , m	DTM _{70F} , m	DTM _{70MC} , m	DTM _{70NF} , m	DTM _{90F} , m	DTM _{ALS} , m
X	1.26	0.46	0.04	0.06	0.06	0.05	0.05	/
Y	0.89	0.29	0.04	0.04	0.04	0.04	0.04	/
XY	1.09	0.38	0.04	0.05	0.05	0.05	0.04	/
Z	0.14	0.16	0.14	0.10	0.09	0.13	0.11	0.18
XYZ	0.89	0.33	0.09	0.07	0.07	0.09	0.07	/

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