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RESEARCH ARTICLE

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How heavy compaction influences the durability of cohesive forest roads in Sweden

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ABSTRACT

Forest roads play a critical role in Sweden's forest transportation network but are increasingly exposed to higher traffic loads and variable environmental conditions. Compaction is widely recognized as an important factor influencing the mechanical behavior of unbound road materials, yet its performance under field conditions on Swedish forest roads remains insufficiently documented. This pilot study evaluates the influence of enhanced compaction on the short-term structural response of a forest road test section in Trosa, Sweden. Two adjacent sections were constructed: one compacted using an 8-ton roller and one left uncompacted. Field measurements included lightweight deflectometer (LWD) testing to determine the dynamic deformation modulus (Evd), road profile measurements using rotating laser leveling, moisture content assessments, and visual inspections. Measurements were conducted during three phases: immediately after construction, after several months of environmental exposure, and after a controlled traffic simulation involving multiple truck passes. The compacted section consistently exhibited higher Evd values than the uncompacted section during all measurement phases, with average differences of approximately 20–24%. Profile measurements and visual observations generally indicated less deformation and more stable surface conditions in the compacted section compared with the uncompacted section. Moisture content measurements showed a negative correlation with Evd values in both sections, highlighting the influence of water content on the measured response. The findings suggest that enhanced compaction may contribute to improved short-term structural behavior of forest road materials under field conditions.

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Climate change; Increased compaction; Forest roads; Light weight deflectometer (LWD); Profile measurements; Traffic loading

1. Introduction

Sweden's extensive network of private roads includes a large number of unpaved forest roads, which are particularly vulnerable to environmental and traffic-related stresses. These roads are frequently exposed to frequent rainfall, freeze–thaw cycles, and increasing traffic due to growing demand for renewable forest products. In addition, recent increases in permissible truck gross weight have further intensified the stress on these roads. Studies have shown that the performance of unpaved roads is strongly influenced by heavy traffic and climatic conditions (Kuttah, 2016; Kuttah & Arvidsson, 2017), with erosion, rutting, and deformation being common failure mechanisms under high loads.

At the same time, the adoption of High-Capacity Vehicles (HCVs) offers potential environmental and logistical benefits. According to Cederstav et al. (2022), HCVs can reduce CO_2 emissions by up to 40% and decrease the number of truck trips by approximately 50%. However, the benefits of these vehicles can only be realized if the supporting road infrastructure has sufficient structural capacity. A large portion of Sweden's unpaved forest road network was constructed according to outdated design standards, without consideration for modern traffic loads. As a result, many roads, including recently built sections, lack the strength and durability to withstand heavier trucks and higher traffic volumes. This creates a clear challenge for sustainable forest transport and highlights the need for targeted road improvement strategies.

One approach to improving road performance is soil improvement through compaction, which is widely recognized in geotechnical engineering. Compaction involves the mechanical densification of soil or road material, typically using rollers or other equipment, to reduce air voids, increase material density, and improve the structural capacity. In forest road construction, compaction is often performed on locally available, unbound materials under less controlled conditions than conventional paved roads. Nevertheless, adequate compaction is critical for enhancing structural performance, reducing rutting and settlement, and mitigating the effects of environmental stresses such as freeze–thaw cycles (Selig, 1982; Holtz & Kovacs, 1981).

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Beyond the influence of compaction on material properties, the performance of forest roads has gained increasing attention due to the growing demand for reliable year-round timber transportation and the challenges associated with climate change. Recent studies have highlighted that road bearing capacity, trafficability, and surface condition are critical factors affecting the efficiency of long-distance timber transport and the continuity of forest product supply chains. Poor road conditions can lead to reduced hauling productivity, increased transportation costs, and traffic restrictions during periods of high moisture content and low bearing capacity. Furthermore, changing precipitation patterns and more frequent extreme weather events are expected to increase the vulnerability of forest roads to rutting, deformation, and drainage-related failures. Consequently, improving road structural performance through appropriate material selection, moisture control, and compaction practices has become an important aspect of sustainable forest road management and transportation logistics. Recent reviews have also emphasized the need for long-term monitoring and climate-resilient road design to maintain road functionality and support efficient timber transport operations (Fraefel et al., 2021; Yuniawati and Andini, 2023; Karjalainen et al., 2025; Pohle and Jaeger, 2025; Rahbarisisakht et al., 2025).

The effectiveness of compaction depends on several factors, including soil type, moisture content, and compaction effort (Barnes, 2000; Das, 1990; Omar et al., 2003; Shaikh, 2021). Key soil characteristics, such as grain-size distribution, particle shape, specific gravity of solids, and the presence of clay minerals, influence the maximum dry density and optimum moisture content (OMC) achievable during compaction. Soil compacted near its OMC typically exhibits higher strength, reduced compressibility, improved CBR, and lower permeability, all of which contribute to enhanced road performance (West, 1976; DiMillio, 1998; Yao & Song, 2023; Barden & Sides, 1970; Fatoyinbo et al., 2024).

While the general benefits of compaction are well documented, there is limited research on its application and performance in Swedish forest roads under realistic traffic and environmental conditions. Most studies focus on laboratory experiments or paved roads, leaving a gap in understanding how compaction practices affect unpaved forest roads subject to high truck loads and variable moisture conditions. This study addresses this gap by evaluating a case contrast between compacted and uncompacted sections of a forest road, examining how heavy compaction influences structural capacity, durability, and soil mechanical properties in situ.

The objective of this research is to develop a scalable compaction approach for forest roads that enhances the structural capacity and resilience to traffic and environmental stresses. By integrating improved compaction practices into road construction and maintenance, the study aims to provide practical insights for maintaining sustainable forest transportation networks under increasing traffic demands and changing climatic conditions.

2. Field assesments methods

To accurately assess the condition of the road sections constructed by Holmen, both immediately after construction and after exposure to weather and traffic conditions, a series of detailed measurements were conducted. These included lightweight deflectometer (LWD) tests, rotating laser level (RLL) profile measurements, moisture content assessments, and visual inspections of both the test sections and the surrounding terrain.

2.1. Light weight deflectometer test

The light weight deflectometer (LWD) is an effective tool for evaluating the structural capacity and overall condition of unbound granular materials used in road construction (Mooney and Miller 2009, Schwartz et al 2018 and Kuttah 2023).

The LWD measurements were conducted using a dynamic plate loading device equipped with a circular loading plate with a diameter of 300 mm. The device applies an impulse load through a falling mass mechanism, generating short-duration dynamic loading representative of traffic-induced stress conditions. The resulting surface deflection was used to calculate the dynamic deformation modulus (Evd).

It is acknowledged that LWD measurements may be influenced by moisture conditions, stress dependency, contact quality, and material heterogeneity, as discussed in previous studies (Grajewski 2025, Kuttah and Persson 2026 and Kuttah and Hindrikes 2026). To reduce variability, measurements were performed using a consistent testing procedure throughout all phases

By applying a load to the surface and measuring the resulting deformation, LWD provides important information about the stiffness of the road. This helps engineers evaluate how well the road can carry traffic without deforming excessively. LWD tests are quick and easy to perform, making them useful for identifying areas that may need maintenance or additional compaction, see Figure 1.

Specifically, the LWD measures the dynamic deformation modulus (Evd) calculated according to Eq. 1, which reflects the ability of the material to resist deformation under dynamic loading. This helps engineers to assess the structural capacity of the road and its ability to carry traffic loads.

$$Evd = 1.5 * r * \sigma / s \qquad \text{(Eq. 1)}$$

Where:

- r: Radius of the loading plate in millimeters (typically 150 mm for a 300 mm plate).
- σ: Mean normal stress under the plate. For a standard 10 kg falling weight, this is 0.1 MN/m^2 (or 0.1 MPa).
- s: Average settlement of the plate, calculated in mm

The LWD measurements were performed to continuously monitor road surface deformations under load,

Figure 1. Application of a lightweight deflectometer (LWD) on the forest road constructed by Holmen and investigated within the project. Photo: Dina Kuttah, VTI.

providing a more detailed understanding of the road's structural capacity under real traffic conditions. The deformations measured with the LWD were used to calculate the dynamic (elastic) deformation modulus (Evd) using the built-in equation in the LWD device (Kuttah 2023).

2.2. Profile measurements using Rotating Laser Level (RLL)

Profile measurements of gravel roads were carried out using a rotating laser level (RLL) system to capture the road surface geometry along transverse sections, see Figure 2. The measurements were conducted by establishing a fixed reference laser plane above the road surface. A receiver mounted on a staff was then used to record elevation readings at predefined positions across the road width.

At each measurement point, the vertical distance between the laser reference plane and the road surface was recorded, enabling the reconstruction of the cross-sectional profile. Measurements were taken at regular intervals along the road section in order to capture spatial variations in surface condition.

The resulting data were used to determine changes in height, slope, and surface irregularities across the road profile. These measurements allow identification of deformation patterns such as rutting, corrugation, and uneven material distribution caused by traffic loading and environmental effects.

The data collected from fixed road profile measurements, taken at regular intervals along the road section (as described in Paragraph 5, "Measurement Layout and Test Points"), and repeated over the study period, provide a basis for more informed decisions regarding road maintenance.

Figure 2. Road profile measurements using Rotating Laser Level (RLL). Photo: Tomas Johansson, SCA.

2.3. Visual inspections of the road sections and the surrounding terrain

Visual inspections of gravel road sections and the surrounding terrain are important to identify surface damage and assess the overall condition of the road. These inspections include checking for common problems such as ruts, potholes, loose gravel and corrugations, and evaluating the effectiveness of drainage. Observing the surrounding terrain is equally important, as factors such as slope, vegetation and water flow can affect the durability of the road. Good drainage is essential to prevent erosion and water damage, so inspectors often look for signs of water accumulation or insufficient runoff.

In this study, the final measurements were conducted under gray and overcast weather conditions with light drizzle and a temperature of approximately 10 °C. Rain had occurred during the week preceding the measurements, and the roadside ditches were filled with water.

3. Study site, road materials and construction

The study was conducted on a forest road located in Trosa in Sweden during the summer of 2023.

The investigated material is representative of the cohesive forest soils frequently encountered in Sweden. These soils often serve as the existing subgrade during construction and are typically retained due to economic and logistical constraints. Although this material type may limit direct generalization to all forest roads, it provides important insight into road performance under challenging moisture-sensitive conditions

The road was divided into two sections: an uncompacted section and a section subjected to enhanced compaction. The experimental workflow involved field assessment of road geometry, surface conditions, and soil characteristics, followed by in situ measurements using lightweight deflectometer and profile measurments to evaluate structural performance. Laboratory tests were also performed to determine key soil properties, including maximum dry density, optimum

moisture content, and particle-size distribution. This section provides a detailed description of the study site, measurement procedures, and analytical methods employed.

3.1. Location of the road sections tested in this study

The forestry company Holmen built its pilot road along an existing forestry road in Trosa (Södermanland County). The pilot road built to test the effect of heavy compaction was denoted as section 2 in this study. This section was subdivided into two test sections, namely, sections: 1 and 2. Section 1, measuring 200 meters, was left uncompacted, while section 2, measuring 150 meters, was compacted. This division allows a comparison of the compaction effect between the two sections.

3.2. Characterization of the tested road materials

Based on laboratory testing, including grain size distribution, Atterberg limits, moisture-density relationship and grain density tests, Figure 3 shows the grain size distribution of the pilot road sections, in accordance with SS-EN 933-1 (2012).

Figure 3 shows that the in-situ material of the tested road in Trosa consists of, on average, about 40% fine-grained material passing sieve #200 (0.075 mm). The grain density was determined to be 2.63 g/cm³, in accordance with SS-EN 1097-6 (2013). When determining the consistency limits at SGI, the samples showed that the material has a liquid limit (LL) of 37% and a plastic limit (PL) of 21.6%, based on SS 027120 (1990) and SS 027121 (1990). This results in a plasticity index (PI) of 15,4%. Compaction properties were determined in accordance with EN 13286-2 (2010) to determine the optimum water ratio and maximum dry density for the materials tested. The compaction test showed that the existing soil achieved a maximum dry density of 1.86 g/cm³ at an optimum water ratio of 13.5%. Note that the values of the index properties quoted are for the average of the two depths.

3.3. Construction process for the road sections

The construction of the pilot road in Trosa, carried out by Holmen's forestry company, began with meticulous planning and the use of compaction equipment that is not typically used in traditional forest road construction in Sweden. In preparation, the contractor watered the road several days before construction, enhancing the material's workability. Moisture content was carefully monitored at multiple locations using a ball test, which confirmed a proper moisture level based on the "thumb roll" method (also called the "feel and appearance" method).

The pilot road sections were constructed along an existing forest road alignment with an average road width of approximately 4–4.5 m. Prior to reshaping, the upper road material layer, approximately 10–15 cm thick, was loosened and redistributed using a motor grader. Existing roadside ditches were maintained to facilitate drainage. The road crown and transverse slope were shaped to promote runoff away from the wheel tracks.

The tested material consisted of locally available unbound granular soil with a relatively high fine-grained fraction (~40% passing the 0.075 mm sieve), corresponding to a cohesive gravelly soil commonly encountered on Swedish forest roads. The subgrade conditions along the investigated sections were visually assessed as relatively uniform, with no visible indication of shallow groundwater during construction. However, elevated ditch water levels were observed during the final measurement phase following prolonged rainfall.

Section 2 was compacted and leveled, whereas Section 1 was only leveled. Compaction of Section 2 was performed using an approximately 8-ton vibratory smooth drum roller (see Figure 4). A total of six roller passes were applied under field conditions representative of operational forest road construction practice. Prior to compaction, the material was moisture-conditioned through watering to approach favorable compaction conditions based on field assessment. The same compaction procedure and number of passes were applied uniformly over the entire Section 2.

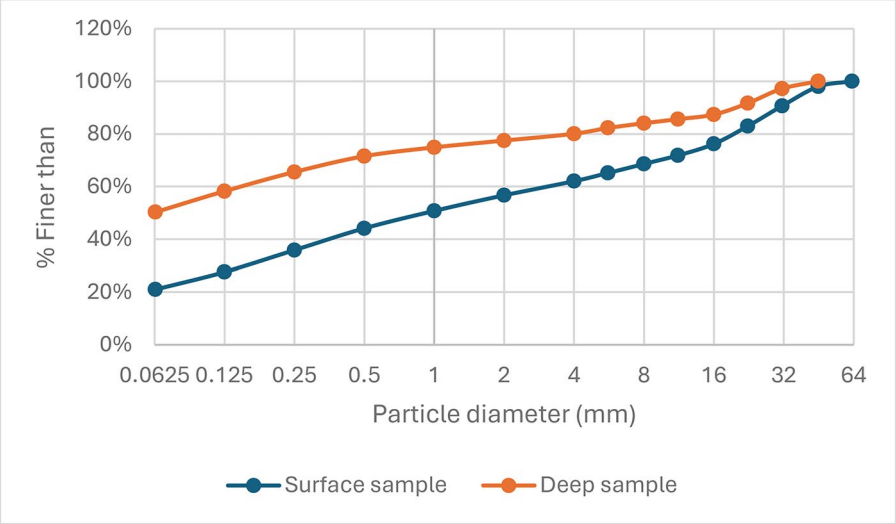

Figure 3. Grain size distribution of two samples collected from the tested road in Trosa.

Compaction was continued until no further visible surface densification was observed.

Although conventional laboratory-based field compaction control indices such as degree of compaction (Is) were not determined during construction, the effectiveness of the compaction process was indirectly evaluated through subsequent LWD stiffness measurements, profile stability observations, and reduced deformation behavior.

Upon completion, the road surface was left to settle for one day before being put into use.

4. Traffic simulation

The traffic simulation was intended primarily to introduce additional controlled loading conditions prior to the final measurements rather than to fully reproduce long-term forest haulage traffic spectra. It should also be noted that the investigated road sections were exposed to actual field traffic and environmental conditions for several months between the initial and final measurement phases. Consequently, the observed road response reflects the combined influence of environmental exposure, operational traffic, and the controlled truck-loading simulation.

The traffic simulation was performed by a truck that made approximately 30 passes on the test sections during this traffic simulation. Note that the traffic simulation was carried out under the supervision of experts from Holmen's forestry company.

The truck used in the traffic simulation has built-in scales that measure the weight on each axle. The weight of the truck used in the traffic simulation is distributed as follows: 8.4 tons at the front, and 9.5 tons and 9.2 tons at the rear, giving a total weight of 27.1 tons, see Figure 5.

The applied truck loading corresponds to approximately 4.6 equivalent single axle loads (ESALs) per pass, based on an 80 kN standard axle and the fourth-power law.

Figure 4. The construction of the pilot road in Trosa, Photo Nils Anders Olsson, Holmen.

5. Measurement layout and test points

5.1. Test points layout

Figure 6 shows the locations where profile measurements and lightweight deflectometer (LWD) tests were conducted at selected points along the test sections.

A total of six profile measurements and fourteen LWD tests were performed during each of the three test phases (initial, intermediate, and final) at different time intervals between these phases. The details of these measurements will be discussed in the following sections.

5.2. Measurement layout

The initial measurements were taken immediately after the road sections were built, just before they were exposed to environmental conditions. The intermediate measurements followed four months later, after weather exposure but before traffic simulation. The final measurements were carried out after the traffic simulation was completed.

During each phase of in-situ testing, measurements followed the layout shown in Figure 6. LWD tests in the initial phase were conducted precisely at the points indicated in Figure 6. However, in the intermediate and final phases, LWD test points were shifted slightly, approximately 30 cm from their original locations, to

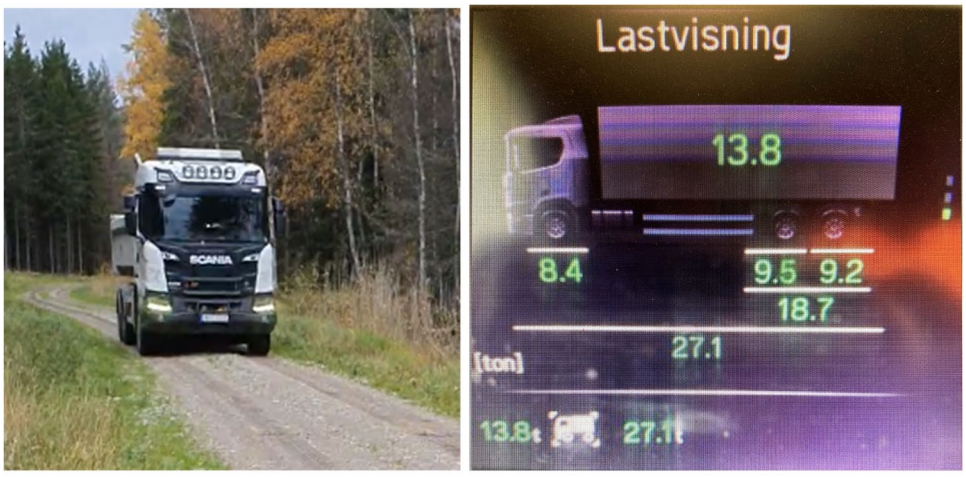

Photo: Andreas Waldemarson, VTI. Photo: Nils Anders Olsson, Holmen.

Figure 5. The traffic simulation included several passes with a fully loaded truck on the pilot road in Trosa.
Photo: Andreas Waldemarson, VTI.Photo: Nils Anders Olsson, Holmen.

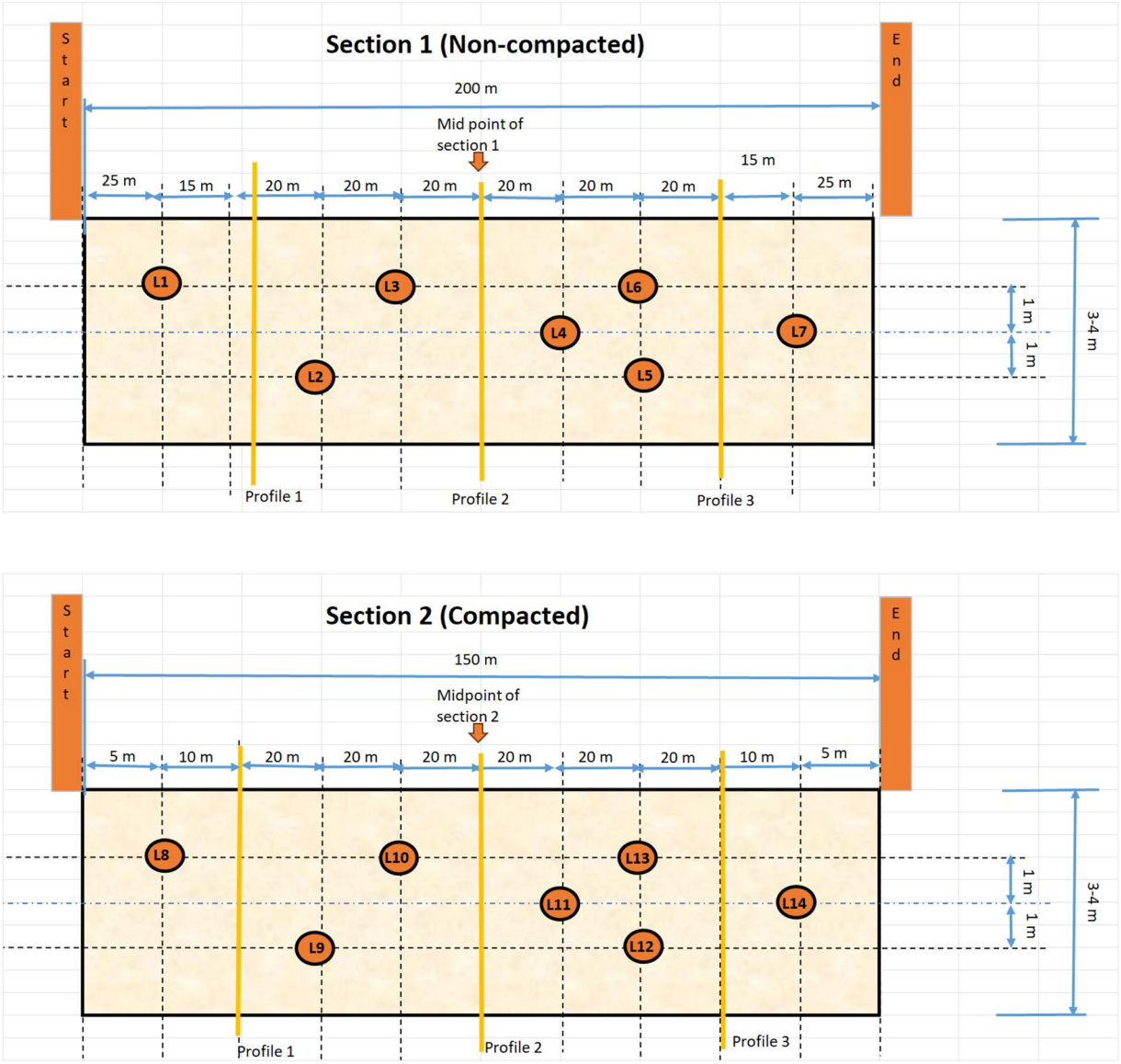

Figure 6. Test points and profile layout for the road sections in Trosa.

prevent recompaction that could occur if tested in the exact same spots. These initial, intermediate, and final measurements establish a baseline for evaluating road performance and identifying potential issues arising from environmental and traffic-related factors.

For this pilot road in Trosa, additional profile measurements were performed during the final phase using advanced UAV drone technology, a road surface measurement vehicle (RST), and rotating laser leveling (RLL). The results of these three methods were compared, revealing minimal mean absolute differences of 1.1 cm between UAV and RST, 1 cm between UAV and RLL, and 0.7 cm between RST and RLL. The detailed findings of this comparison are presented by Kuttah and Waldemarson (2024).

6. Results

6.1. Light weight deflectometer and moisture content measurements

Figures 7–9 present the results of the LWD test from the initial, intermediate and final measurement phases for Sections 1 and 2. The dotted lines with corresponding Evd values represent the average Evd (MPa) for each section and measurement occasion.

Figures 7–9 demonstrate that compaction of Section 2 significantly improved the LWD measurements compared with the uncompacted Section 1. The improvement was consistently observed throughout the testing period, with Evd values increasing by 20.46% during the initial measurements, 24.16% during the intermediate measurements, and 20.53% during the final measurements relative to the corresponding values measured in the uncompacted section. These results clearly demonstrate the positive effect of compaction on the stiffness and structural capacity of the tested pavement sections.

Table 1 presents the average water content measured during the initial, intermediate, and final testing stages for the two road sections. It is shown that the moisture content in the uncompacted Section 1 was 6.15% during the initial stage, increasing to 10.69% in the intermediate stage and 10.18% in the final stage. In the compacted Section 2, the corresponding values were 8.89%, 11.30%, and 9.51%, respectively.

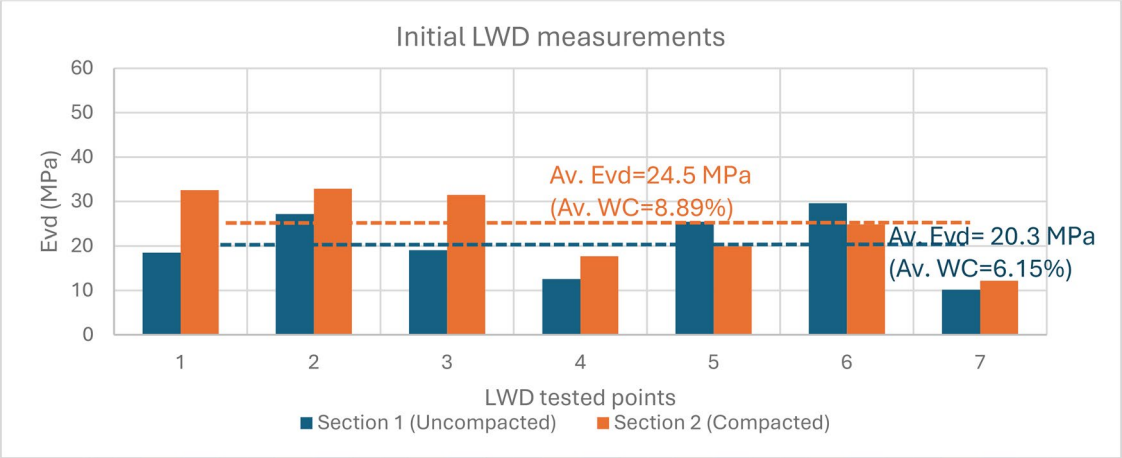

Figure 7. The Evd values from the initial LWD measurements for the tested road sections.

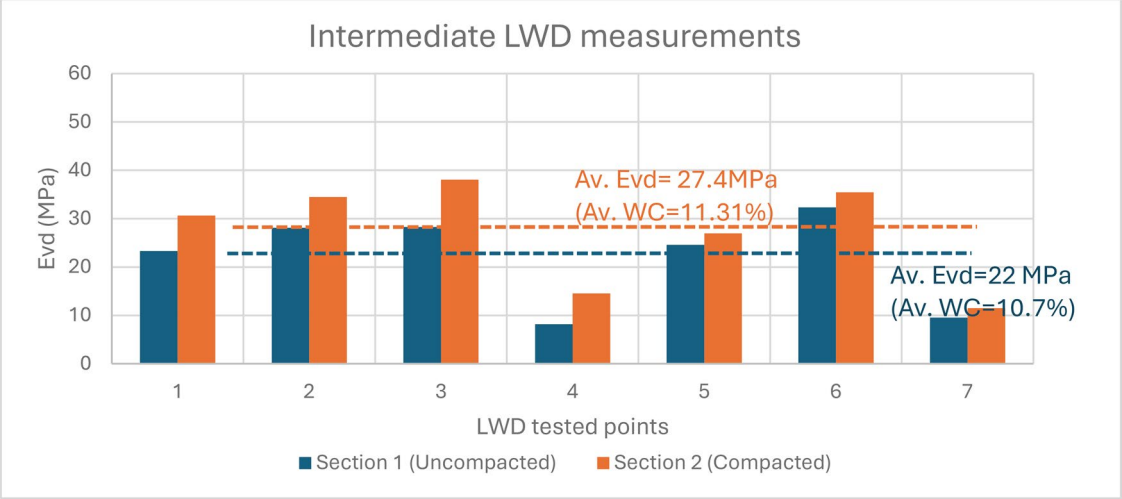

Figure 8. The Evd values from the intermediate LWD measurements for the tested road sections.

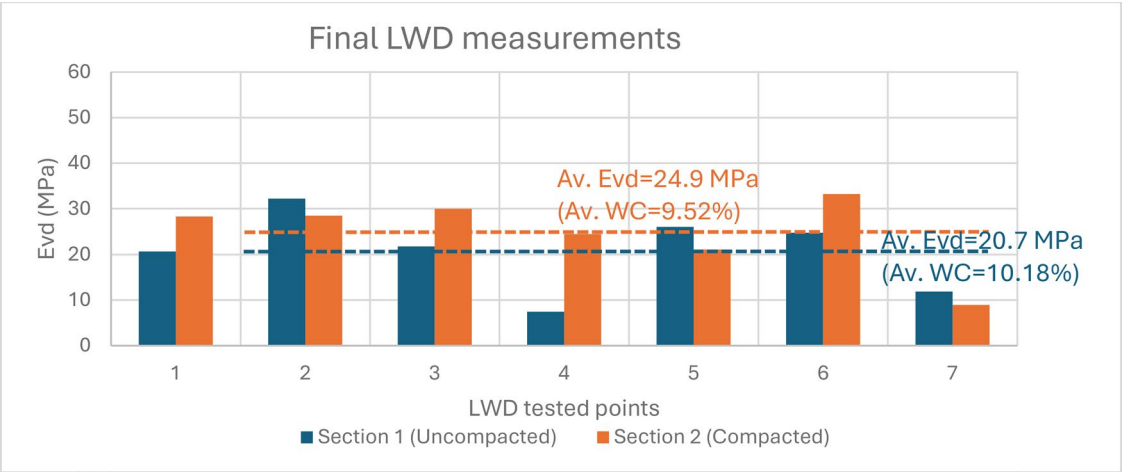

Figure 9. The Evd values from the final LWD measurements for the tested road sections.

Although the average water contents in the compacted section were slightly higher than those measured in the uncompacted section during the three testing stages, the compacted section consistently exhibited substantially higher Evd values. This demonstrates that the stiffness response of the pavement is governed not only by moisture content but also by the improved soil structure resulting from compaction. By reducing the void ratio, increasing particle interlock, and enhancing load transfer between soil particles, compaction produces a denser and stiffer material capable of maintaining higher stiffness even under relatively wet conditions.

More importantly, the changes in water content over time reveal the beneficial effect of compaction on

Table 1. The water content values from the initial, intermediate and final measurements for the tested road sections.

Section 1 - (Uncompacted)				Section 2 (Compacted)			
Measurement point ID	Average WC (%) from the initial measurements	Average WC (%) from the intermediate measurements	Average WC (%) from the final measurements	Measurement point ID	Average WC (%) from the initial measurements	Average WC (%) from the intermediate measurements	Average WC (%) from the final measurements
L2	4.9	7.19	8.02	L9		9.04	7.32
L3		7.41	7.8	L10		7.58	6.07
L4	7.39	15.1	13.26	L11	5.03	10.88	10.46
L5		7.1	8.51	L12		7.65	6.04
L6		8.04	6.47	L13		6.78	7.88
L7		18.99	15.59	L14	12.76	25.97	20.25
Average for the section	6.15	10.7	10.18	Average for the section	8.89	11.31	9.52

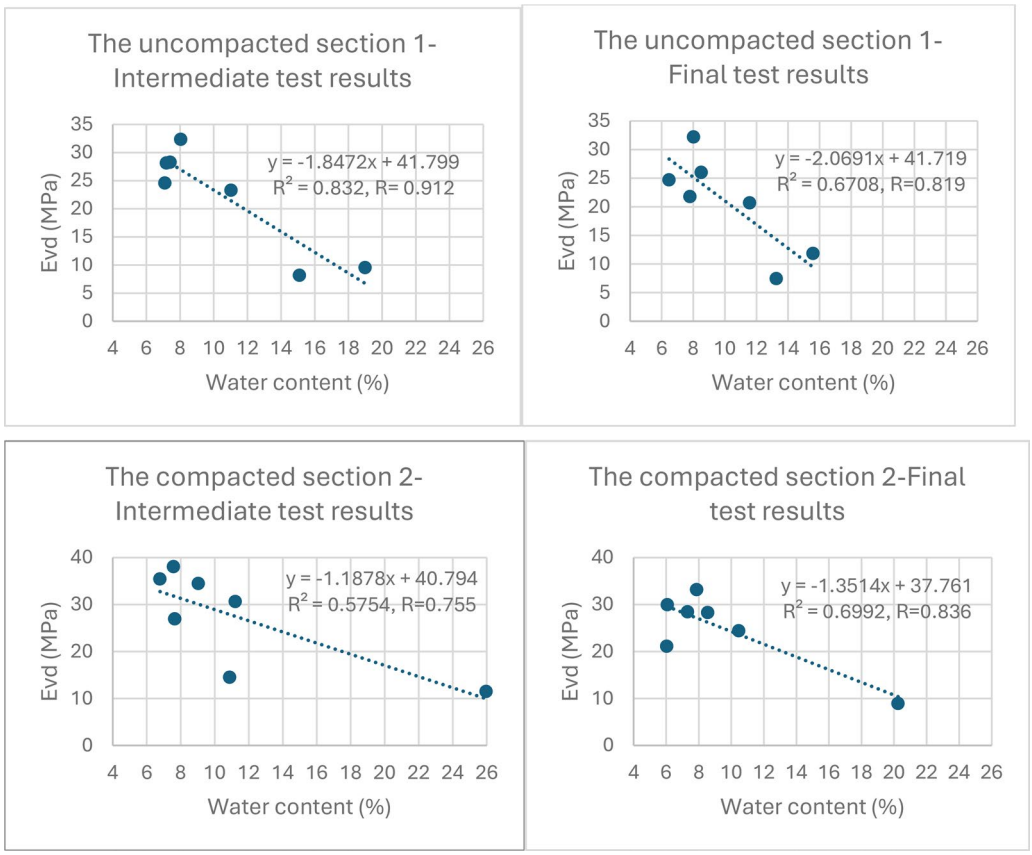

Figure 10. Relationship between the measured Evd values and the corresponding water contents in the compacted and uncompacted sections at the different testing stages.

moisture resistance. Relative to the initial stage, the water content in the uncompacted section increased by 4.6% and 4% during the intermediate and final stages, respectively, whereas the corresponding increases in the compacted section were only 2.4% and 0.6%. These results indicate that, despite its slightly higher initial moisture content, the compacted layer experienced considerably smaller increases in moisture following rainfall and/or groundwater infiltration. This suggests that compaction reduced the susceptibility of the road layer to additional moisture ingress by decreasing its porosity and limiting the connectivity of pore spaces. Consequently, compacted road materials generally exhibit lower permeability and greater resistance to water infiltration than uncompacted materials, a behaviour that is well established in pavement engineering.

Figure 10 illustrates the relationship between the measured Evd values and the corresponding water contents for the compacted and uncompacted sections. The results show a clear inverse relationship, with increasing water content generally associated with lower Evd values, as confirmed by the negative Pearson correlation coefficients. These findings demonstrate that moisture content significantly influences the stiffness response measured by the LWD and further highlight the importance of effective drainage and moisture control in maintaining the structural performance of cohesive forest road materials.

The observed inverse relationship between water content and Evd is consistent with the findings of Ampadu and Arthur (2022), who reported that the degree of saturation has a significant influence on the mechanical behaviour of compacted pavement materials and can diminish the benefits of compaction despite the application of high compactive effort.

In addition, the water-content coefficients in the relationships between water content and Evd are relatively higher for the uncompacted layer (1.85 and 2.07) than for the compacted layer (1.19 and 1.35). Since these coefficients represent the rate at which Evd decreases with increasing water content, the results indicate that Evd in the uncompacted layer is more sensitive to changes in water content. Specifically, Evd decreases approximately 1.5 times faster in the uncompacted layer than in the compacted layer, indicating that compaction improves the layer's resistance to moisture-induced reductions in stiffness.

Nevertheless, the consistently higher Evd values measured in the compacted section throughout the testing period demonstrate that the structural improvements achieved through compaction outweighed the adverse effects of the observed moisture variations.

6.2. Profile measurements

Profile measurements were carried out for road sections both before and after they were exposed to weather and traffic impacts, providing a comparative analysis of changes over time. The data highlights variations in height, cross-sectional shape and material distribution across different sections of the road. These measurements, shown in Figures 11 and 12 for sections 1 and 2 respectively, help to assess potential problems such as uneven wear, rutting or material displacement, which are crucial for evaluating the characteristics of the road and determining the necessary maintenance or improvement measures.

It can be seen that the compacted section 2, shown in Figure 12, experienced fewer changes in its profiles over the three measurement occasions compared to the

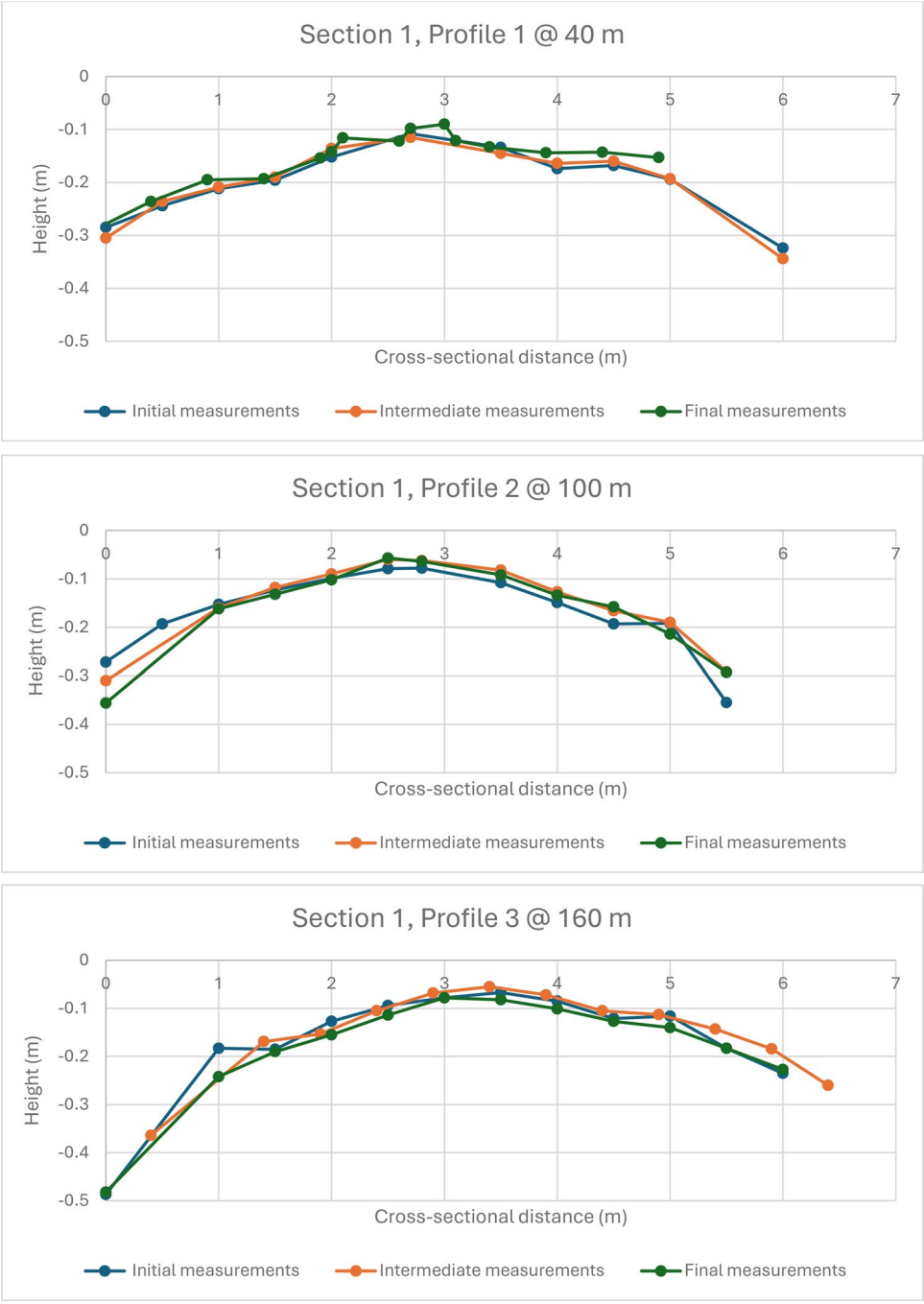

Figure 11. Initial, intermediate and final profile measurements for road section 1 built by Holmen in Trosa.

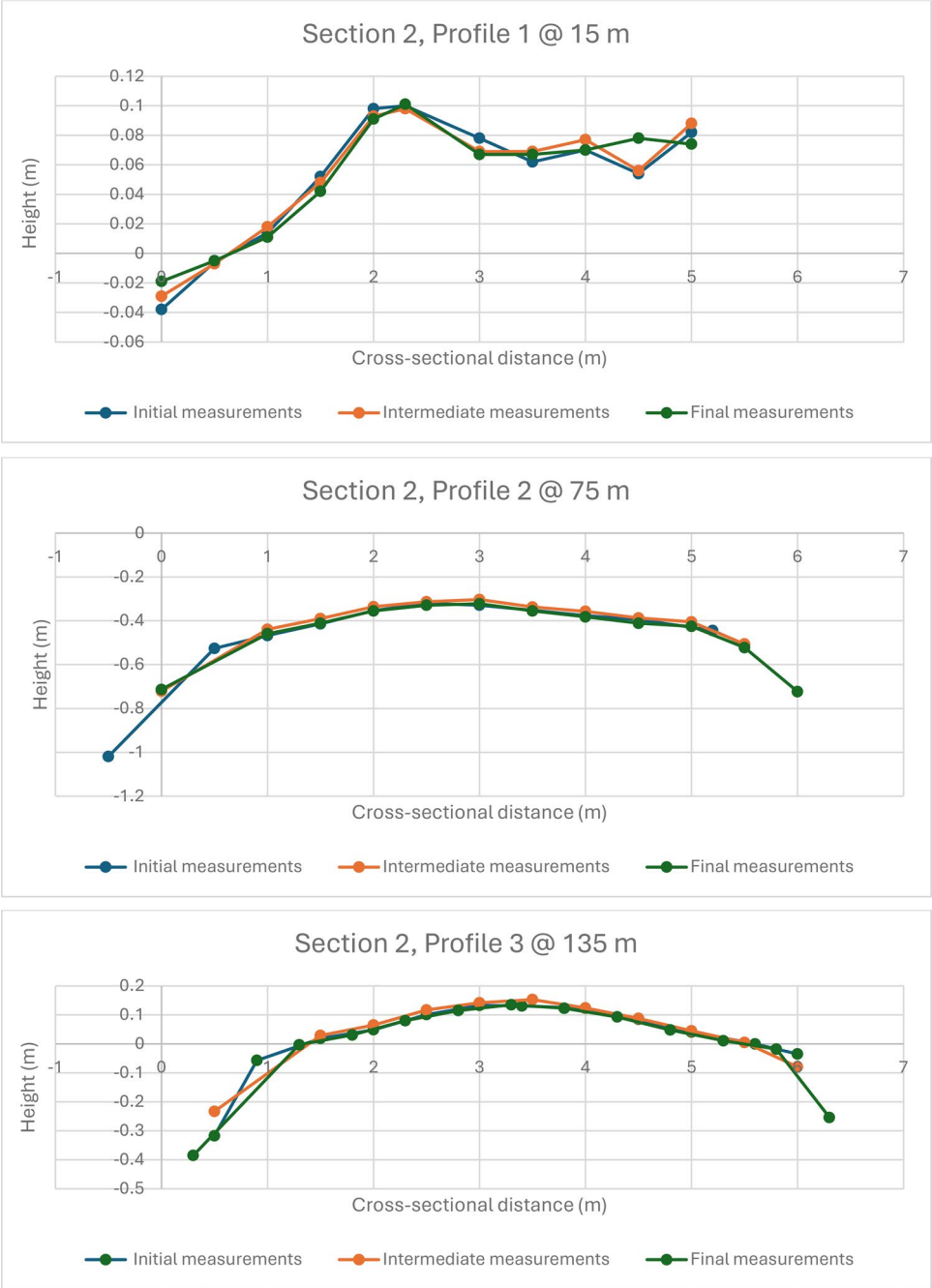

Figure 12. Initial, intermediate and final profile measurements for road section 2 built by Holmen in Trosa.

corresponding profile measurements for the uncompacted section 1, shown in Figure 11.

The uncompacted section exhibited greater rut development, and localized material displacement between measurement phases compared with the compacted section. In contrast, the compacted section generally maintained a more stable transverse profile geometry and exhibited smaller observable changes in wheel-track elevation and surface shape.

6.3. Visual inspection of the tested sections

In section 1, which was not compacted, grass was present in the center of the road, and muddy ruts were observed in the wheel tracks. Indications of ditches were observed between profiles 0/040 and 0/045 on the right wheel track (i.e., profiles located 40 m and 45 m from the start point of the section, respectively; the same notation applies to similar designations). The cross section followed the alignment, and no corrugation was observed. Rutting occurred along the alignment, with no dusting and occasional areas of loose gravel, mainly in the center of the road and along the roadside, see Figure 13.

In section 2, which was compacted, grass was also present in the center of the road and muddy ruts were observed. Ditches were noted between profiles 0/090 and 0/105. The cross section followed the alignment, and no corrugation was observed. A feature that may represent a pothole was observed at profile 0/150 in the right wheel track. No noticeable dusting was observed, and loose gravel was mainly present in the center of the road and along the roadside, see Figure 14.

Figure 13. Final visual inspection of road section 1 constructed by Holmen in Trosa. Photo: Andreas Waldemarson, VTI.

Figure 14. Final visual inspection of road section 2 constructed by Holmen in Trosa. Photo: Andreas Waldemarson, VTI.

6.4. Economic (cost-benefit) analysis

The compacted section exhibited an average increase in Evd of approximately 4.24 MPa (20.52%) compared with the uncompacted reference section. According to the project-level economic assessment, this improvement corresponded to an estimated cost of approximately 3.41 SEK per meter of road and increased Evd unit, while optimized operational conditions were estimated to reduce this value further to approximately 0.73 SEK per meter of road and increased Evd unit. These findings suggest that enhanced compaction may represent a relatively cost-effective method for improving the short-term structural performance of forest roads under suitable field conditions.

A detailed description of the economic evaluation methodology, including assumptions, cost components, and calculation procedures, is provided in Kuttah et al. (2025).

7. Discussion

The study confirms that heavy compaction clearly improves the structural performance of forest roads, making them more resilient to increased traffic loads and environmental conditions. The compacted section exhibited a 20.46% increase in LWD stiffness in the initial phase, 24.16% in the intermediate phase, and 20.53% in the final phase compared to the uncompacted section. The observed inverse relationship between water content and Evd is consistent with the the fact that compaction makes the pavement more resistant to taking in water as shown by the consistently lower water contents for the compacted pavement compared with the uncompacted for all three stages.

In addition, the water-content coefficients in the relationships between water content and Evd are relatively higher for the uncompacted layer (1.85 and 2.07) than for the compacted layer (1.19 and 1.35). Since these coefficients represent the rate at which Evd decreases with increasing water content, the results indicate that Evd in the uncompacted layer is more sensitive to changes in water content. Specifically, Evd decreases approximately 1.5 times faster in the uncompacted layer than in the compacted layer, indicating that compaction improves the layer's resistance to moisture-induced reductions in stiffness.

The increase in Evd values observed during the intermediate phase may be associated with seasonal wetting-drying cycles that can lead to densification or rearrangement of particles in unbound materials. However, after the traffic simulation, the final measurements showed a decline in Evd values for both the compacted and uncompacted sections compared to the intermediate measurements. Although this decrease was observed in both sections, the compacted section maintained average higher Evd values than the uncompacted section throughout the testing phases. This difference indicates that the compacted section retained a higher structural stiffness under repeated loading, suggesting improved resistance to traffic-induced deterioration compared with the uncompacted section.

It is important to highlight that the cross-sectional profile can influence the distribution of water within the road structure by affecting surface drainage and the movement of water across the road width. In general, sections with a well-defined crown promote

runoff toward the shoulders, reducing water retention within the wheel paths and the road surface. Conversely, flatter or locally depressed areas may allow water to accumulate for longer periods, resulting in higher moisture contents.

In the present study, variations in water content among the measurement locations, as shown in Table 1, may therefore be partly attributed to differences in the cross-sectional profiles and their drainage characteristics. However, water content is also influenced by several other factors, including local material properties, compaction level, precipitation history, evaporation conditions, and traffic-induced changes in the road surface. Consequently, while the cross-sectional geometry likely contributed to some of the observed moisture variations, its individual effect could not be isolated from the other influencing factors based on the available data.

On average, the compacted section exhibited less deformation over time and maintained a more stable cross-sectional shape, whereas the uncompacted section showed greater rutting and material displacement. Visual inspections further supported these findings, with the uncompacted section showing more pronounced muddy wheel tracks, embankment formation, and surface irregularities compared to the compacted section. Overall, the LWD data indicates that the compacted section exhibited a higher structural capacity, as reflected in the Evd values, compared to the uncompacted section. To improve the understanding and application of Evd values, further research is needed to investigate how they change with moisture content, material type, and loading. A deeper understanding of these interactions can provide valuable insights into how road materials affect structural capacity and how Evd values can be effectively used to assess gravel road conditions. Leveraging Evd in road condition assessments can enable more precise and informed maintenance decisions, ultimately contributing to more sustainable road management strategies.

As Swedish forest roads face greater challenges due to heavier loads and climate variations, adopting advanced compaction techniques will be essential for ensuring long-term durability and resilience.

The findings of this study have important implications for forest operations and timber transportation. Previous research has shown that the bearing capacity and condition of forest roads directly influence timber hauling efficiency, transportation costs, vehicle accessibility, and the continuity of wood supply chains. Roads with inadequate bearing capacity can restrict heavy vehicle access, reduce transport productivity, increase cycle times, and lead to higher operational costs, particularly during periods of elevated moisture content and reduced trafficability. Conversely, improving road stiffness and resistance to deformation can enhance year-round accessibility and support more efficient long-distance timber transport operations. Recent studies have emphasized that forest road bearing capacity is a critical factor for maintaining a continuous flow of roundwood to mills and reducing transportation costs, which often represent a substantial share of total harvesting expenses. The higher Evd values, reduced rutting, and improved surface stability observed in the compacted section therefore suggest potential operational benefits through improved trafficability, reduced maintenance requirements, and greater resilience to increasing traffic loads and climate-related stresses. These findings support ongoing efforts to develop climate-resilient forest road networks capable of sustaining efficient forest operations and reliable timber transportation under changing environmental conditions.

8. Conclusion and recommendations

The study concludes that heavy compaction generally improves the structural performance and resilience of forest roads, enhancing their ability to withstand increased traffic loads and environmental stresses, such as precipitation and seasonal temperature variations. The compacted section showed average higher LWD stiffness across all phases, demonstrating a notable improvement in structural capacity compared to the uncompacted section. Moisture content analysis showed a negative correlation with stiffness, indicating that water content may influence Evd values. In the observed sections, the compacted areas generally exhibited less deformation, reduced rutting, and more stable surface profiles compared with the uncompacted areas. These findings suggest that compaction can play a role in enhancing the short-term structural performance of forest roads. Future research is needed to more investigate the relationships between Evd, material properties, and repeated loading, which could support the development of more robust maintenance and assessment strategies.

The findings indicate that LWD measurements may provide a practical field tool for identifying sections with reduced structural capacity and elevated moisture sensitivity. Development of operational Evd threshold values for maintenance planning represents an important future research direction.

Furthermore, the present study primarily evaluates short-term structural response under field conditions. Long-term monitoring over multiple seasons, including freeze–thaw cycles and repeated traffic loading, is required to better assess the durability benefits of enhanced compaction.

In addition, replication of the methodology across multiple forest roads with varying material types, drainage conditions, and traffic intensities would improve the robustness and general applicability of the findings.

Future studies should also incorporate assessments of longitudinal surface irregularities in addition to transverse profile measurements to provide a more comprehensive evaluation of forest road performance.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Data will be made available on request.

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