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Article

Development of the new method for assessing condition of forest road surface

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Abstract: Regarding number of vehicles, forest roads are characterized by low traffic intensity, but on the other hand great values of ground pressure between wheels of timber truck units and forest road surface occur, often with pressures values above 80 kN which additionally causes damage of the upper and lower forest road layer. There are currently several methods for assessing condition of a forest road surface which are mainly used for assessing state of public roads, but can be used in forestry as well. Assessing condition of forest road surface was done by measuring vibrations with a specially developed software for Android OS installed on a Huawei MediaPad 7 Lite. Software measured vibrations in all three axes, coordinates of device, speed of the vehicle and time. Aim of this research was to determine accuracy of collected data so that this method can be used for scientific and practical purposes. Research was carried out on the segment of a forest road during driving a vehicle equipped with a measuring device. Tests were performed in both driving direction of the forest road segment with different measuring frequencies, tyre inflation pressures and driving speeds. Values of vibrations were classified and translated on a map of forest road together with devices' measured coordinates. Vibration values were compared with places of recorded forest road surface damages. Research results show no significant difference in vibration values between 1 Hz and 10 Hz of measurement frequencies. Based on the analysis of collected data and obtained results, it is clear that it is possible to assess the condition of a forest road surface by measuring vibrations. The greatest values of vibrations were recorded on the most damaged parts of the forest road. Vibrations do not depend on tyre inflation pressure, but ranges of vibrations are decreasing with decreasing driving speed. Accuracy of collected data depends on GPS signal quality, so it is recommended that each segment of forest road is recorded twice so that location of damages on forest road can be confirmed with certainty.

Keywords: forest road surface; forest road damage; vibration measurements; vibration software

1. Introduction

The Forest roads are characterized by low traffic intensity [1], but high values of contact pressures between wheels and forest roads commonly exceeding 80 kN [2] cause damage to upper and lower forest road layers [3]. Due to the damage caused by forest truck assembly (FTA) axles' overload and the lack of a proper maintenance of the forest road, during a certain period of time, loss of availability to a particular forest area may occur [4, 5].

Improper or excessive use of forest roads refers to their use in adverse weather conditions, conditions of disturbed road body stability, traffic by unauthorized means, and disregard of the legal limitations of the maximum permissible loads. By observing traffic intensity and road construction interaction, Reissinger [6] concludes that traffic with its vibrations negatively affects construction materials of the road, and points out that this negative impact is proportional to the vehicle weight or the pressure of the vehicle on the wheels. Dietz et al. [7] deal with the problem of forest road amortization and conclude that due to the traffic load and natural factors, bearing capacity of the road is being constantly reduced.

Underhill [8] considers that main causes of forest road damage are: climatic factors, road geometry, errors in road design, quality of built-in materials, valid standards to be met when performing operations, type and frequency of maintenance, surface and ground drainage, frequency and type of traffic, age of the road.

Pentek et al. [9] in procedures that are considered as improper or excessive use of forest roads include the traffic of overloaded trucks in timber transport, transportation of construction machinery and stone materials, the use of forest roads after strong and prolonged rain or snow, driving of forestry or construction vehicles with caterpillars or with chains on wheels, improper operations in timber harvesting, driving at speeds higher than allowed.

Due to the aforementioned causes of road damage, forest roads after construction should be regularly maintained to enable the fulfilment of all the tasks in forest management plans. Quality and timely maintenance extends the life of the forest road, reduces vehicles' costs and the frequency of their repairs, makes the forest road transit throughout the year and increases the safety of all traffic participants [10]. Proper maintenance also reduces the negative impact of forest roads on natural resources and allows their long-term use. This ensures investments in planning, designing and building a forest road network [11].

According to Klassen [12] and Pellegrini et al. [13] current maintenance of roads is necessary to preserve their trafficability and enable the proper functioning of drainage systems. Non-maintained roads impact vehicle damage, increase fuel consumption and fuel costs [14]. Many studies show that road maintenance not only improves the state of forest roads, but reduces costs of timber transportation [15, 16].

Nunamaker et al. [17] point out that the first rule of maintaining upper road layer is by reducing road use in wet conditions. For road use throughout the year, it is advisable to avoid traffic of heavy vehicles such as forest trucks during heavy rainfall. According to Wells [18], forest roads should not be used in wet conditions, since they are the most likely cause of damage and in addition, the productivity of timber transport will be reduced.

Grace and Clinton [19] write about the problem of identifying those forest roads which state is critical and require reconstruction, and on which aforementioned reconstruction process will be profitable due to the amount of reconstruction costs and at the same time reduction of the environmental impact together with additional benefits from their use. The criteria for identification differ depending on whether it is a forest economic road primarily intended for timber transport and access of forest machines and workers to the forest, or forest roads that are primarily used for tourist and recreational purposes.

Every year, in the maintenance of forest roads, significant financial resources are invested, and in practice single-criteria analyses are often used, which may be subjective and include only those criteria that suit the user. Coulter et al. [20] emphasize the need to use the multi-criteria decision methods for reconstruction and maintenance of forest roads. The authors believe that the new method will provide a consistent and unbiased approach to the ranking of investments in the constructed network of primary forest traffic infrastructure, as well as an appropriate tool for determining the viability of forest road reconstruction.

Papa et al. [10] emphasize the need to develop a new methodology for continuous monitoring of the condition of forest roads and road structures. Based on the sample of a certain type and intensity, it is necessary to be able to assess the present state of the forest road, to make appropriate conclusions and to plan the maintenance of forest roads at the level of the management unit.

There are a number of methods for assessing the condition of the road construction, which are primarily used for the estimation of public road conditions, but their use can also be found in forestry. Krishna Rao [21] cites the methods of assessing the condition (damage) of the road construction, and divides them into two groups:

- Subjective methods;

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- Objective methods.

Subjective assessment methods are based on individual filling in forms, where road users and experts, based on examining a particular road segment, make a judgment of its status. Estimates are most often ranging from 0 to 5, where 0 indicates the worst state of the road, while grade 5 indicates good road condition.

Krishna Rao [21], Douangphachanh and Oneyama [14], as well as many other authors argue that subjective methods are extremely expensive due to the time necessary to collect data and the constant presence of researchers and field experts during the research implementation.

The objective methods of assessing pavement condition use different types of measuring instruments, from analogue to digital for collecting data. Some of the methods are:

- Classic method of terrain surveying – impractical and expensive method.
- The use of the Dipstick Profiler – provides extremely precise data of road profile level, but the measurements are extremely time-consuming and are therefore primarily used to control the condition of the aerial platforms and to calibrate other more complex instruments;
- Test wheel – a »fifth wheel« freely oscillating when driving a vehicle and recording the road's unevenness on a paper;
- Road roughness meters (Response type road roughness meters – RTRRMs) – instruments that indirectly measure the longitudinal road profile so that the device records the relative distance between the vehicle chassis and the center of the rear axle;
- Road profile measuring devices – devices that accurately record longitudinal and transverse road profiles and road damage while using contact or non-contact sensor systems. Non-contact sensor systems by laser or ultrasonic devices record road profiles. In addition to the use of sensors, such systems also use video cameras, and segments of the measured road are processed using computer programs. Such devices are called the Integrated Pavement Analysis Units or the Automatic Road Analyser. These devices are expensive because they require special vehicle fitting, the development of specialized computer programs, and are therefore often used only to calibrate the RTRRM devices. Such devices were used by Dawson and Killer [22] and Svenson [23] in their research. The device used by Dawson and Killer [22] is an ultrasonic radar that has the ability to capture the condition the lower road layer as well. The computer program used with these devices, as the final output, gives the IRI value along with other road profile recordings.

Figure 1. Laser system for recording road condition (Source: Svenson [23]).

In order to simplify road condition estimates, many authors started using accelerometers instead of specialized devices, where the vibration recorded determines the condition of road pavements. Gonzalez et al. [24] put the accelerometer in the test vehicle to estimate the condition of the road, and conclude that based on recorded data the condition of the road construction can be estimated. Similar conclusions are made by Erikson et al. [25]. Mohan et al. [26] use a mobile phone instead of a specialized vibration measuring devices, whereby the embedded sensors determine the state of the road and the traffic. Strazdins et al. [27] use smartphones with an Android operating system, where the smartphone embedded accelerometers and simple algorithms determine the location of impact holes on the road. Tai et al. [28] and Perttunen et al. [29] determine the state of the road based on the analysis of vibration frequencies that they recorded using a smartphone. Douangphachanh and Oneyama [14] explore the ability to determine road conditions using smartphones by means of vibration measures and conclude that using smartphones significantly simplifies the road condition estimation methods.

The state of the road construction will be measured by vibrations, so one goal of the research is to determine the accuracy of measured data both for scientific and practical application. It is important to emphasize that in this research the vibrations were not measured from the ergonomic aspect, but with the aim of determining road condition based on the changes in vibration values.

2. Materials and Methods

The estimation of the upper forest road layer condition was performed by measuring vibrations on the 300 m long segment of a forest road in the Training and Research Center Zalesina, Faculty of Forestry University of Zagreb, Croatia. The selected forest road segment was on a flat terrain without a longitudinal slope, and with two curves, one at the beginning, the other at the end of the segment. Pavement damages of the road segment were recorded in the driving directions of the vehicle's wheels. Two impact holes were recorded: the first after 70 m from the beginning of the test track in the length of 1 m and of 10 cm depth from the roadway surface, and the other 200 m from the beginning of the test track in the length of 0.6 m and of 6 cm depth from the roadway surface.

Figure 2. Impact hole on the segment of forest road.

Vibrations were measured using a Huawei MediaPad 7 Lite tablet with a built-in three-way accelerometer MMA8452Q (Table 1) and a specially developed application for the Android platform. This measurement system has been used due to low purchase price, measuring speed and data collection method. Namely, when measuring vibrations, the goal was to measure the relative vibration values, that is, their change with respect to changes in condition of the upper forest road layer.

Data recorded by the application:

- Vibrations in three axes (x, y, z);
- Vehicle location (GPS coordinates);

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- Driving speed, km/h;
- Number of satellites;
- Longitudinal road inclination between two recorded points, ˚;
- Travelled distance between two recorded points, m.

Table 1. Technical characteristics of MMA8452Q accelerometer (Source: Anon. 2015).

Measurement range, m/s²	± 39,24
Sensitivity (m/s²)	51,19
Sensitivity accuracy, %	± 2,64
Sensitivity change vs. temperature, %/˚C	± 0,008
Accuracy, m/s²	± 0,2
Accuracy change vs. temperature, (m/s²)/˚C	± 0,0015
Operating temperature range, ˚C	-40 ˚C – 85 ˚C
Vibrations range, Hz	1,56 – 800

During field measurements, the tablet was placed in the windshield of the vehicle (Lada Niva). The measurements were recorded during 12 times of repeated driving on the same forest road segment in both directions at a constant speed of 20 km/h. Tyre inflation pressure was 2.5 bar. At the moment of starting the application, the device is connected with location satellites and automatically starts recording, regardless of the vehicle movement.

In addition, the influence of different driving speeds (20, 40 and 60 km/h) and various tyre pressures (2, 2.5 and 3 bar) to vibration values were also investigated.

Vibrations were measured in all three axes and WAS data was calculated based on the measured values. During all measurements, the vibration recording frequency was 10 Hz, while the GPS coordinate frequency was 1 Hz. All measurements were made in real time. The collected data was sorted into a database in MS Excel, while the ArcGIS 9.3 computer program was used for graphic display of field measurements. Field data was compiled in tables for following statistical analysis. The software package used to create the database was Microsoft Office Excel 2007, and the statistical data processing was performed in the StatSoft STATISTICA 8 programme package.

Descriptive statistics was used to describe the set of observational data sets (independent variables), where different measures of the central tendency were calculated, and the median and arithmetic mean with the standard deviation were chosen.

3. .Results

First field test refers to the vibration measurements at multiple passes (12 times) on the same forest road segment in both directions and at a constant driving speed of 20 km/h, with a 2.5 bar of tyre inflation pressure. Vibrations were measured at a frequency of 10 Hz and a total of 6844 vibration measurement data were collected for each axis. From the obtained data, the vibration total value was calculated for each reading.

Table 2 shows the measurement results with basic statistical values. The mean vibration total value was 9.85 m/s² with a standard deviation of 0.50 m/s², i.e. the vibration total value ranged from 6.6 m/s² to 13.2 m/s².

Subsequently, vibration measurement was performed at different frequencies.

5 Hz frequency values were obtained by taking every second measurement from the vibration total value data at a frequency of 10 Hz.

The same procedure followed for maintaining data at 2 Hz vibration frequency, i.e. by taking each fifth measurement from the vibration total value data at a frequency of 10 Hz. When determining the total vibration frequency at 1 Hz, each tenth measurement from the vibration total value data at a frequency of 10 Hz was taken.

By comparing the basic statistical distributors, it is apparent that the mean vibration total value remains constant, regardless of the frequency of the readings. Standard deviation, the highest measurable vibration total value, and the data range are reduced by decreasing the frequency of reading. However, if it is assumed that the highest vibration total values can indicate damage of roadway, then it can be concluded that the peak values of vibration can be best detected at a frequency of 10 Hz.

Table 2. Statistical data of measuring total vibration values at different reading frequencies.

Frequency		10 Hz	5 Hz	2 Hz	1 Hz
No. of measurements		6484	3241	1293	643
VTV Average		9.85	9.85	9.85	9.85
VTV Median		9.81	9.81	9.82	9.80
VTV Maximum	m/s^2	13.2	13.2	12.4	11.5
VTV Minimum		6.6	6.6	8.4	8.9
VTV Standard deviation		0.50	0.45	0.35	0.28
Measuring time	s	648.4	648.2	646.5	643.0
Velocity	km/h	19.99	19.99	20.05	20.16

Each measurement of the vibration total value is associated with the GPS coordinate of the measuring point; the data were then plotted on the map of the forest area by ArcGIS 9.3 computer program.

Figure 3A shows the position of the forest road segments with all measured data of the vibration total values during vehicle movement at a reading frequency of 10 Hz. There is a noticeable data dispersion from the forest road route. Therefore, from the graphic representation in Figure 3A, with all the data of vibration measurements, it is impossible to determine the accurate position of the forest road damage.

Since the vibration total values range at 10 Hz readings, from 6.6 m/s^2 to 13.2 m/s^2, for further consideration, values from the upper third of the data range i.e. all vibration total values greater than 11 m/s^2 are displayed (Figure 3B). A grouping of values in two sets around the position of impact holes on the forest road is evident. It is impossible to precisely determine the location of the road damage due to the deviation of the measuring points GPS coordinates from the forest road route.

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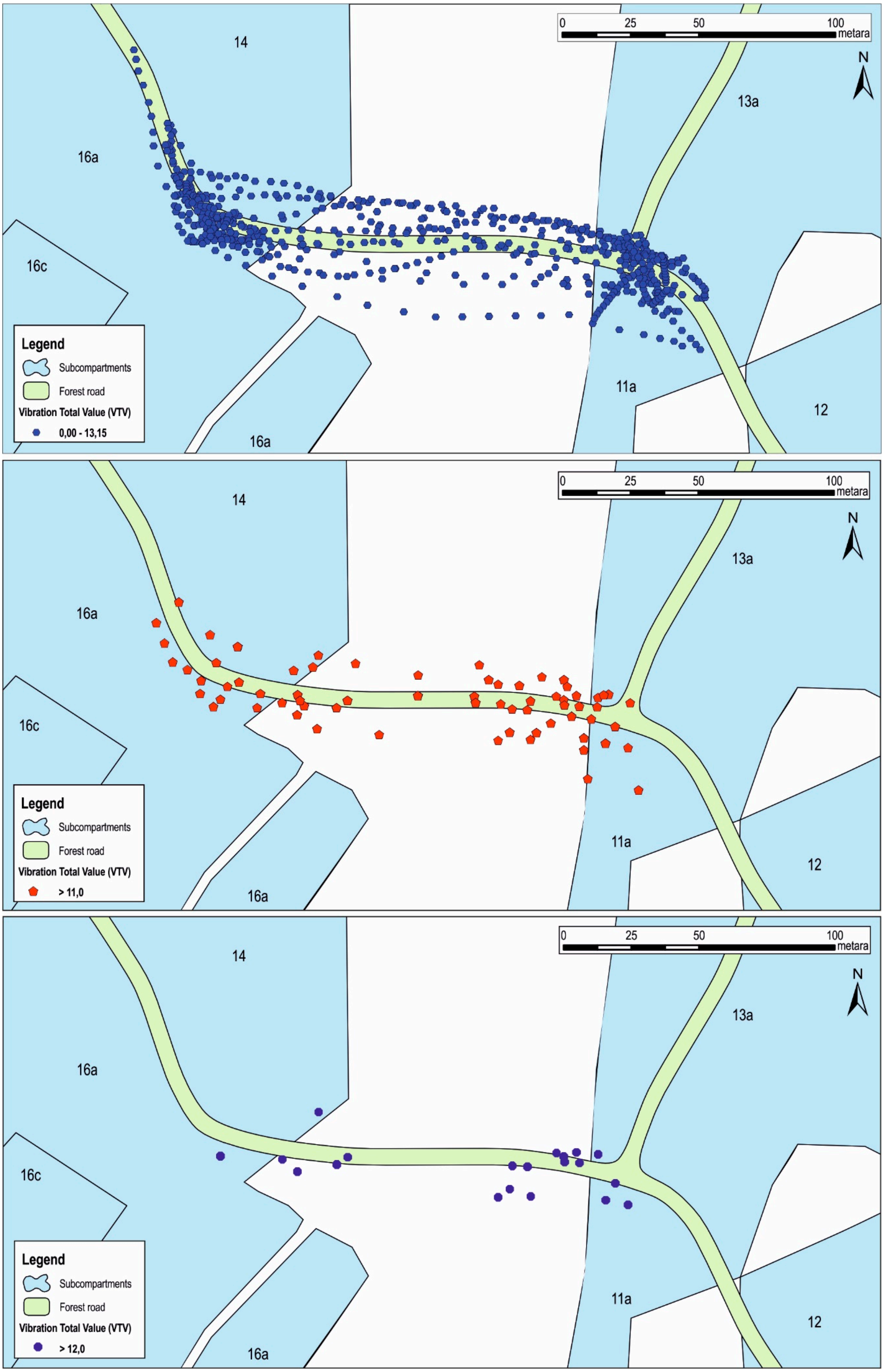

Figure 3. Vibration total values on forest road segments.

The next step is to display measured data of the vibration total value greater than 12 m/s², i.e. peak vibration values (Figure 3C). In the total data range mentioned above, the vibration total value of 12 m/s² up to a maximum of 13.2 m/s² is represented in the upper 20% of measured data range.

In comparison, there is now a much more visible grouping of data at damaged roadway of forest road segment. At the same time, the greater the damage (larger dimensions of the impact hole), the greater number of peaks of vibration total values.

The impact of different driving speeds (20, 40 and 60 km/h) and different tyre inflation pressures (2, 2.5 and 3 bar) on the vibration total value, during vehicle's movement along the same forest road segment was determined. At each vehicle passing, one of the variables changed, for example, with 2 bar tyre inflation pressure initial driving speed was 20 km/h, then 40 km/h and ultimately 60 km/h. The procedure was repeated after raising the tyre inflation pressure to 2.5 bar or to 3 bar. The recording frequency was 10 Hz.

Table 3 shows average vibration total values and standard deviations for various experiments with regard to tyre inflation pressure and vehicle driving speed.

It is noticeable that all values increase with increase of driving speed and tyre inflation pressure. The reasons for that lie in the fact that at higher driving speeds higher vibration values of the vehicle structure occur and are transmitted to the measuring device. At a lower tyre inflation pressure of 2 bar, the tyre is »softer« and it absorbs vibrations of the forest road better so the vibrations created by road damage cannot be sufficiently determined. With »harder«, 3-bar inflation pressure tyres, the vibration total value is increased as a result of tyres' adhere loss.

On the basis of the analysis of the influence of different driving speeds and tyre inflation pressures on the vibration total value of the vehicle in order to estimate the condition of the forest road, the vehicle speed of 20 km/h is recommended, with a tyre inflation pressure of 2.5 bar.

Table 3. Statistical data of measuring vibration total values at different driving speeds and tyre inflation pressures.

Driving speed km/h	Values	Tyre inflation pressure, bar		
		2	2,5	3
20	No. of measurements	530	514	511
40		271	277	278
60		186	187	184
20	VTV Average m/s2	9.77	9.85	9.93
40		9.89	9.90	9.96
60		9.91	9.94	10.40
20	VTV Standard deviation m/s2	0.34	0.38	0.43
40		0.65	0.67	0.66
60		0.66	0.67	0.68

4. Discussion

Based on the results presented, it is possible to estimate the condition of the forest road by vibration. The vibration values depend on the speed of the vehicle and tyres' inflation pressure. This is somewhat in line with the Douangphachanh and Oneyama [14] findings, which conclude that the speed of the test vehicle, the type of the vehicle and the type of vibration measuring device are affected by the vibrations recorded. Also, Gillespie et al. [30] and Sayers et al. [31] state the accuracy of vibration measurements is highly dependent on the vehicle type, driving speed, vehicle load (mass), tyre type and inflation pressure.

Based on the analysis of the influence of different driving speeds and different tyre inflation pressures on the vibration total value of the vehicle, and in order to estimate the condition of the forest road, the vehicle speed of 20 km/h is recommended, with tyres' inflation pressure of 2.5 bar. However, in the further development of the assessing method by means of vibration measurements it is necessary to investigate the impact of different types of vehicle for the accuracy of the measurement.

Strazdins et al. [29] find that there are significant differences in the accuracy of the collected data at different frequency of data recording. Research results indicate that only with 10 Hz vibration frequency measurements it is possible to connect peak values with forest road damage. In that case, peak values represent the upper 20% of values in the total data range.

During measuring vibration with an Android application, as well as during data processing, certain errors were detected. The biggest problem is the GPS accuracy because the data collection depends mostly on the quality of the GPS signal. Along with the recorded satisfactory number of satellites during the measurement (5 to 6 satellites) there is a large deviation of the coordinates for each measuring point. It should also be noted that the research was carried out during the vegetation period when trees' crowns beside the forest road also produce a significant effect on the accuracy of the vehicle's positioning. It is therefore recommended that each section of the road is recorded at least two times, in order to certify the spatial distribution of the forest road damage.

Also another error in the Android application was detected concerning data of the driving speed and travelled distance. Since the travelled distance and driving speed are recalculated using GPS coordinates of measuring points, same inaccuracies occurred as described previously. Therefore, the travelled distance and driving speed are displayed on the basis of the data obtained from the vehicle.

The newly developed Android application also measures the longitudinal slope of the forest road between two measuring points. Since this research was conducted in flat terrain, it was not possible to give a judgment on the validity of recorded data on the longitudinal slope of the road forest. Therefore, it is also necessary to conduct a research in uneven terrain and on a forest road with a longitudinal inclination. However, one can assume that measurement error, due to computer calculation of longitudinal inclination based on measuring points coordinates, is highly likely to occur.

Errors were also manifested by inadequate data recording formats. Sometimes the vibration value data, irrelevant of the axis type, were recorded in the x. x. xxxx format. Such record format cannot be used when performing data analysis. The amount of incorrect data per individual test was below 0.5%.

Due to the above mentioned errors and shortcomings, it is essential to verify recorded data before conducting the analysis, so unrealistic results can be avoided. In order to use the enhanced application for future use, it is necessary to:

- Use a more precise GPS device or plan field measurements during the winter period when trees' crowns will not represent a possible disturbance.
- Remove the above mentioned inadequate data recording formats that occur during recording.
- Enable the application user to independently choose the beginning and the ending of the recording, rather than an automatically starting measurements as soon as device is connected to the satellites location.
- Possibility of selecting recording frequency.
- Remove route and slope data from the application, as unrealistic data is recorded, the size of recorded files is reduced, which will further simplify data analysis.

5. Conclusions

The state of the forest road construction can be evaluated by vibration measurements in a simple and inexpensive way of collecting data.

For the further development of the method, it is necessary to determine the condition of the forest road pavement structure, also pavement surfacing type using a subjective (descriptive method) estimation and by vibration measurements of the same area, in order to determine the accuracy and reliability of the method. Furthermore, it is necessary to identify all types of damage in the forest road and based on the description of the damage, measure the vibration in the same area in order to determine the vibration differences for each type of road construction damages.

In future studies, it is necessary to determine the correlation between subjective and objective methods for evaluating the state of forest roads in order to create road damage classes depending on different terrain categories. Furthermore, it is necessary to investigate the impact of different smart phones and vehicle types on vibration values, and to determine the optimal sample size (recording forest road segment length).

By using GIS as a tool, collected data of the forest road construction state, various thematic maps for a particular forest area or management unit can be created. Thematic maps on forest road damages, along with the further method development and the categorization of forest roads based on the state of the road construction, can serve forestry experts and practitioners for further planning of forest road maintenance operations and as a basis for calculating required investments.

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References

1. Fertal, D. Transport intensity in forest hauling road. *Zapravy Lesnickeho Vyzkumu* **1994**, *2*, 34-37.
2. Šušnjar, M.; Horvat, D.; Pandur, Z.; Zorić, M. [Axle Load Determination of Truck with Trailer and Truck with Semitrailer for Wood Transportation]. *Croat J For Eng* **2015**, *32*, 379–388. Croatian
3. Trzcinski, G.; Kaczmaryk S. Estimation of carrying capacity of slag and gravel forest road pavements. *Croat J For Eng* **2006**, 27, 27-36. Available online: http://www.crojfe.com/r/i/trzcinski.pdf
4. Keller, G.; Sherar, J. Low-Volume Roads Engineering - Best Management Practices Field Guide. *US Agency for International Development*, **2003**, 1-129.
5. Özturk, T.; Şentürk, N. Analisis of Pavement Construction on a Sample Forest Road - Section in Sariyer Region. *Istanbul Üniversitesi Orman Fakültesi Dergisi. Seri A*. **2009**, *59*, 55-70.
6. Reissinger, G. Forest road building over marshy soils. Committee on Forest Working Techniques and Training of Forest Workers. *Symposium on Forest Road Construction and Maintenance Techniques, Sess. 9, Sopron (Hungary), 6-8 Sep 1972, Sopron, Hungary*, **1972**.
7. Dietz, P.; Knigge, W.; Löffler, H. Walderschließung. *Eine Lehrbuch für Studium und Praxis unter besonderer Berücksichtigung des Waldwegebaus*. Verlag Paul Parey, Hamburg und Berlin, Deutschland, **1984**. German
8. Underhill, R. *Life Cycle Maintenance of Low Volume Roads in the Alice Springs Region*. PhD thesis. University of Southern Queensland: Faculty of Engineering and Surveying, **2004**.
9. Pentek, T.; Nevečerel, H.; Ecimović, T.; Lepoglavec, K.; Papa, I.; Tomašić, Ž. [Strategic Planning of Forest Road Network in Croatia – Analysis of Present Situation as Basis of Future Analysis]. *N Meh Šum*, **2014**, *35*, 63–78. Croatian. Available online: http://www.jnms.eu/strategijsko-planiranje-sumskih-prometnica-republici-hrvatskoj-rasclamba-postojecega-stanja-podloga-buduce-aktivnosti/
10. Papa, I.; Pentek, T.; Lepoglavec, K.; Nevečerel, H.; Poršinsky, T.; Tomašić, Ž. Methodology of development of detailed primary forest traffic infrastructure register as the basis for forest roads maintenance planning and optimization. *Šum list,* **2015,** *7-8*, 311-328. Croatian. Available from: http://www.sumari.hr/sumlist/pdf/201503110.pdf
11. Anon. *Forest roads manual*. Oregon department of forestry - State forest program, **2000**, 1-6.
12. Klassen, A. Planning, location, survey, construction and maintenance for low – impact forest roads. *Center for Forestry Education and Training, Forestry Department of Republic of Indonesia*, **2006**, 1-82.
13. Pellegrini, M.; Grigolato, S.; Cavalli, R. Spatial multi – criteria decision process to define maintenance priorities of forest road network: an application in the Italian alpine region. *Croat J For Eng* **2013**, *34*, 31–42. Available online: http://www.crojfe.com/r/i/pelegrini_31-42.pdf
14. Douangphachanh, V.; Oneyama, H. A Study on the Use of Smartphones for road Roughness Condition Estimation. *Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 9*, **2013**. Available online: https://pdfs.semanticscholar.org/1458/ee4b0bc04ad62e0173779295d275957138ed.pdf
15. Feng, Z.W.; Douglas, R.A. Logging truck vehicle performance prediction for efficient resource transportation system planning: Computer Modelling Approach. *J For Eng* **1993**, *4*, 7–18. Available online: https://journals.lib.unb.ca/index.php/IJFE/article/viewFile/10050/10306

16. Talbot, B.; Nitteberg, M. Using transloading times in determining the effect of reduced road standards on the delivered cost of timber. *Proceedings of the FORMEC 2011 Symposium: Pushing the boundaries with research and innovation in forest engineering, Graz, Austria*, **2011**. 1-7.
17. Nunamaker, C.; LeBlanc, J.; Nakamura, G.; Valachovic, Y. Forest stewardship series 17: forest roads. *University of California, Division of agriculture and natural resources*, **2007**, 1-14.
18. Wells, C.H. Forest harvesting roads: meeting operational, social and environmental needs with efficiency and economy. Proceedings of the International conference on the Applying Reduced Impact Logging to Advance Sustainable Forest Management in Kuching, Malaysia, **2002**, 70–90.
19. Grace, J.M.; Clinton, B.D. *Forest road management to protect soil and water*. American society of agricultural and biological engineers (ASABE). Annual meeting presentation, **2006**, 1-14. Available online: https://www.srs.fs.usda.gov/pubs/ja/ja_grace030.pdf
20. Coulter, E.D.; Coakley, J.; Sessions, J. The analytic hierarchy process: a tutorial for use in prioritizing forest road investments to minimize environmental effects. *Int J For Eng* **2006**, *17*, 51–69. Available online: https://journals.lib.unb.ca/index.php/IJFE/article/view/5696/6701
21. Krishna Rao, K.V. Methods of Measuring Distress. Transportation Systems Engineering, *Department of Civil Engineering, IIT Bombay*, **2012**, 1-11.
22. Dawson, A.; Killer, D. Roads under timber traffic. *University of Nottingham & Forestry Civil Engineering*, **2009**, 1-22.
23. Svenson, G. The impact of road characteristics on fuel consumption for timber trucks. In Ackerman P, Ham H, Gleasure E (eds) Proceedings of 4th Forest Engineering Conference: Innovation in Forest Engineering – Adapting to Structural Change. Stellenbosch University, **2011**.
24. González, A.; O'brien, E.J.; Li, Y.Y.; Cashell, K. The use of vehicle acceleration measurements to estimate road roughness. *Vehicle System Dynamics*, **2008**, *46*, 483–499, DOI: 10.1080/00423110701485050
25. Eriksson, J.; Girod, L.; Hull, B.; Newton, R.; Madden, S.; Balakrishnan, H. The pothole patrol: using a mobile sensor network for road surface monitoring, *Paper Proceedings of the Eastern Asia Society for Transportation Studies presented at the Sixth International Conference on Mobile System, Applications and Services, Breckenridge, Colorado, United States, 17-20 June* **2008**.
26. Mohan, P.; Padmanabhan, V.N.; Ramjee, R. Nericell: Rich Monitoring of Road and Traffic Condition using Mobile Smartphones. *Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems*, **2008**, 323–336.
27. Strazdins, G.; Mednis, A.; Kanonirs, G.; Zviedris, R.; Selavo, L. Towards Vehicular Sensor Networks with Android Smartphones for Road Surface Monitoring. *Paper presented at the 2nd International Workshop on Networks of Cooperating Objects, Chicago, USA, April 11* **2011**.
28. Tai, Y.; Chan, C.; Hsu, J.Y. Automatic road anomaly detection using smart mobile device. Paper presented at the 2010 Conference on Technologies and Applications of Artificial Intelligence, Hsinchu, Taiwan, 18-20 November **2010**. Available online: https://pdfs.semanticscholar.org/0669/241928cbdf9f847075db299cdd467a6345f2.pdf
29. Perttunen, M.; Mazhelis, O.; Cong, F.; Kauppila, M.; Leppänen, T.; Kantola, J.; Collin, J.; Pirttikangas, S.; Haverinen, J.; Ristaniemi, T. Distributed road surface condition monitoring using mobile phones. *Ubiquitous Intelligence and Computing*, **2011**, 64–78. ISBN: 978-3-642-23640-2
30. Gillespie, T.D.; Sayers, M.W.; Segel, L. Calibration of Response-Type Road Roughness Measuring Systems. *I' NCHRP Rept. No. 228*, **1980**.
31. Sayers, M.W.; Gillespie, T.D.; Paterson, W.D. Guidelines for the Conduct and Calibration of Road Roughness Measurements. *World Bank Technical Paper No. 46, The World Bank, Washington DC*, **1986**.