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

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Preliminary note

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

A new method for assessing condition of forest road surface layers by vibration measurements is analysed in the paper. The research was conducted on a forest road segment while driving a vehicle equipped with a measuring device for determining vibrations in all three axes, vehicle position, vehicle speed, and time. Tests were performed in both driving directions of the forest road segment using different measuring frequencies, tyre inflation pressures, and driving speeds. The recording frequency of 10 Hz, vehicle speed of 20 km/h, and tyre inflation pressure of 2 bars, can be recommended based on the forest road surface measurement results.

Key words:

forest road surface, forest road damage, vibration measurement, recording frequency

Prethodno priopćenje

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Razvoj nove metode za procjenu stanja površinskog sloja šumskih cesta

U radu se analizira nova metoda za procjenu stanja površinskog sloja šumskih cesta mjerenjem vibracija. Istraživanje je provedeno na dijelu šumske ceste tijekom vožnje vozila opremljenog mjernim uređajem kojim se mjere vibracije u sve tri osi, položaj i brzina vozila te vrijeme. Ispitivanja su provedena u oba smjera vožnje na dijelu ceste s različitim frekvencijama mjerenja, tlakovima u gumama i brzinama vožnje. Na temelju rezultata mjerenja stanja površinskog sloja šumske ceste preporučuje se frekvencija snimanja od 10 Hz, brzina vozila od 20 km/h te tlak u gumama od 2 bara.

Ključne riječi:

površinski sloj šumske ceste, oštećenja šumske ceste, mjerenje vibracija, frekvencija snimanja

Vorherige Mitteilung

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Entwicklung einer neuen Methode zur Beurteilung des Zustands der Oberflächenschicht von Forststraßen

In der Abhandlung wird die neue Methode zur Beurteilung des Zustands der Oberflächenschicht von Forststraßen durch Messung der Vibrationen analysiert. Die Untersuchung wurde auf einem Teil der Forststraße während der Fahrt des mit einem Messgerät ausgerüsteten Fahrzeugs durchgeführt, mit welchem die Vibrationen aller drei Achsen, die Lage und die Geschwindigkeit des Fahrzeugs sowie die Zeit gemessen werden. Die Untersuchungen wurden in beide Fahrtrichtungen auf dem Teil mit unterschiedlichen Messfrequenzen, Reifendrücken und Fahrgeschwindigkeiten durchgeführt. Aufgrund der Messergebnisse des Zustands der Oberflächenschicht von Forststraßen empfiehlt sich eine Messfrequenz von 10 Hz, eine Fahrgeschwindigkeit von 20 km/h sowie ein Reifendruck von 2 Bar.

Schlüsselwörter:

Oberflächenschicht der Forststraße, Beschädigung der Forststraße, Vibrationsmessung, Aufnahmefrequenz

1. Introduction

Although forest roads are characterized by low intensity of traffic [1], upper and lower layers of forest roads [2] can be damaged by high values of contact pressures between wheels and forest road surface, commonly exceeding 80 kN [3]. Due to damage caused by excessive axle loads of forest truck assemblies (FTA), and the lack of proper forest road maintenance, forest areas affected in this way may over time become fully inaccessible [4, 5].

Improper or excessive use of forest roads implies their use in adverse weather and when road body stability has been impaired, use of unauthorized means of transport, and disregard to maximum permissible load restrictions. When considering the interaction between the traffic (traffic load) and pavement structure, Reissinger [6] concludes that traffic with its vibrations negatively affects road binding materials, and points out that this negative impact is proportional to the vehicle weight or the pressure imposed by the vehicle onto its wheels. Dietz *et al.* [7] deal with the forest road depreciation issue and conclude that the bearing capacity of roads is constantly reducing, due to the vehicle wheel action (traffic load) and natural factors.

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 road works, type and frequency of maintenance, surface and subsurface drainage, frequency and type of traffic, and age of the road.

According to Pentek et al. [9], the procedures considered as an improper or excessive use of forest roads include the traffic of overloaded trucks in timber transport, transport of construction machinery and stone materials, and use of forest roads after strong and prolonged rain or snow.

Due to the aforementioned causes of road damage, forest roads should be regularly maintained to enable fulfilment of all tasks contained in forest management plans. Good-quality and timely maintenance extends the life of the forest road, reduces vehicle costs and the need for frequent repairs, makes the forest road fit for transport throughout the year, and increases safety of all participants in traffic [10].

Unmaintained roads facilitate vehicle damage, while also increasing fuel consumption and fuel costs [11]. Many studies show that road maintenance not only improves the state of forest roads, but also reduces cost of timber transport [12, 13]. Significant financial resources are invested in forest road maintenance every year, and single-criteria analyses are often used in practice, although they may be subjective and include only those criteria that suit the user. Coulter et al. [14] emphasize the need to use the multi-criteria decision methods for the reconstruction and maintenance of forest roads. 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 should be possible to assess the present state of a forest road, to make appropriate conclusions, and to plan forest road maintenance activities at the level of management units.

A number of methods are currently available worldwide for assessing condition of road pavement structures. These methods are primarily used for estimating condition of public roads, but they can also be applied in forestry. Krishna Rao [15] considers methods for assessing condition (damage) of road pavement structures, and divides them into subjective methods and objective methods.

Subjective assessment methods are based on appropriate forms filled in by road users and experts who state their opinion on a particular road segment, based on road inspections. Krishna Rao [15], Douangphachanh and Oneyama [11], as well as many other authors, argue that subjective methods are extremely expensive due to the time necessary to collect data and the constant on-site presence of researchers and field experts during such inspections.

Figure 1. Laser system for recording road condition, [17])

In objective pavement-assessment methods, various types of measuring instruments (analogue and digital) are used for collecting data. Some recent methods include:

- The use of *Dipstick Profiler* – provides extremely precise data of road profile level, but the measurements are extremely time-consuming and are therefore primarily used to control condition of airfield runways, and to calibrate other more complex instruments;
- 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 centre of the rear axle;
- Road profile measuring devices – devices that accurately record longitudinal and transverse road profiles and road damage. No-contact sensor systems involving laser or ultrasonic devices are used to record road profiles. In addition to 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 Analysers.* These devices are expensive because they require special adjustments to testing vehicles and development of specialized computer programs. Such devices were used by Dawson and Killer [16] and Svenson [17] in their research.

In order to simplify road condition estimates, many authors have started to use accelerometers instead of specialized devices. In the case of accelerometers, road pavement condition is determined by recording vibrations. Gonzalez et al. [18] placed such accelerometer in the test vehicle to estimate road condition, and concluded that road pavement condition can be effectively be estimated based on the data recorded in this way. They established that pavement structure condition can be assessed based on data records. The possibility of using a fleet of vehicles for parallel analysis of pavement condition has also been successfully tested. This method is far more efficient compared to the use of one vehicle only and, furthermore, the existing public sector vehicle fleets can be used in the testing.

Erikson et al. [19] developed the mobile sensing system for detecting and reporting road potholes. Seven taxi cars were equipped with a Soekris 4801 computer, external GPS, and 3-axis accelerometers. The cars travelled over 9.000 km and, during that time, 174 km of road were covered with ten or more repeated passes. Manual inspection of reported potholes revealed the detection accuracy of over 90%.

Mohan et al. [20] used smartphones with the integrated 3 axis accelerometers for the determination of bumps and potholes on road surface. They tested vibrations at different vehicle speeds and they empirically determined that low speeds (< 25 km/h) are a good indicator of bumps and potholes.

Strazdins et al. [21] used smartphones with an Android operating system, where the smartphone embedded accelerometers and simple algorithms were used to determine location of potholes. Experiments were carried out on the test track using 2 different vehicles, and each experiment consisted of three laps only.

Douangphachanh and Oneyama [11] explored the possibility to determine road condition by means of vibration measurements using smartphones and concluded that road condition estimation method has been greatly simplified by he use of smartphones. The experiment was conducted using 2 Toyota vehicles on the total road length of 159 km. It was established that the relationship between the acceleration data from smartphones and road roughness condition is linear.

Lanjewar et al. [22] also used smartphone sensors for the detection of potholes. It was established that the relationship between the acceleration data from smartphones and road roughness condition is linear. Measurement accuracy is greatly influences by vehicle speed, i.e. it is desirable to conduct measurements at the speed of less than 30 km/h.

The aim of this paper is to evaluate possibilities for determining condition of forest road pavement structures by measuring vibrations using a tablet with a built-in accelerometer. The impact of the reading frequency, vehicle speed, and tyre pressure will be determined by repeated driving of the testing vehicle on the forest road segment. The most favourable measurement settings have to be defined in order to ensure a sufficiently accurate assessment of the forest road pavement damage. The results of the research should be compared with the aforementioned surveys that were carried out on paved public roads, the aim being to determine possible differences that occur on macadam forest roads.

2. Research methods and research location

2.1. Description of research locations

Condition of the upper layer of the forest road was assessed 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 is situated on a flat terrain without longitudinal slope, and with two curves, one at the beginning, and the other at the end of the segment. Pavement damage at the road segment was recorded at the vehicle wheel driving directions. Two potholes were registered: the first one, 1 m in length and 10 cm in depth, was observed 70 m after the beginning of the test track, and the other one, 0.6 m in length and 6 cm in depth, was registered 200 m after the beginning of the test track.

Figure 2. Pothole on a forest road segment

2.2. Research methods

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 was selected based on the low purchase price, measuring speed, and data collection method. Namely, when measuring vibrations, the goal was to measure relative vibration values, that is, their change with respect to changes in condition of the top forest road layer. The following data were recorded by the application:

- Vibrations in three axes (x, y, z)
- Vehicle location (GPS coordinates)
- 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/s^2]	± 39.24
Sensitivity [m/s^2]	51.19
Sensitivity accuracy [%]	± 2.64
Sensitivity change vs. temperature [%/°C]	± 0.008
Accuracy [m/s^2]	± 0.2
Accuracy change vs. temperature [(m/s^2)/°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 bars. At the start of of the application, the device was connected with location satellites and it automatically started recording, regardless of 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) on vibration values was also investigated.

Vibrations were measured in all three axes and the WAS (Weighted Acceleration Sum) value 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 were entered in a MS Excel database, while the ArcGIS 9.3 computer program was used for graphic display of field measurements. Field data were entered in tables for the ensuing statistical analysis. The software package used to create the database was Microsoft Office Excel 2007, and the statistical data processing was performed by means of the StatSoft STATISTICA 8 programme package.

3. Research results

The first field test refers to vibration measurements at multiple passes (12 times) along the same forest road segment in both directions at a constant driving speed of 20 km/h, with the tyre pressure of 2.5 bars. Vibrations were measured at a frequency of 10 Hz and a total of 6844 vibration measurement data were collected for each axis. The obtained data were used to calculate the vibration total value (VTV) for each reading.

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

Subsequently, vibration measurements were compared at various 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 was used to determine total vibration values at the frequency of 2 Hz, 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 was taken from the vibration total value data at a frequency of 10 Hz.

By comparing basic statistical indicators, 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, reduce with the reduction of the reading frequency. However, if it is assumed that the highest vibration total values can indicate damage to roadway, it can be concluded that peak vibration values can best be detected at a frequency of 10 Hz. Strazdins et al. [21] reported that there are significant differences in the accuracy of the data collected at various

Table 2. Statistical data for total vibration values at various reading frequencies

No. of measurements		6484	3241	1293	643
Frequency	[Hz]	10	5	2	1
VTV average	[m/s^2]	9.85	9.85	9.85	9.85
VTV median		9.81	9.81	9.82	9.80
VTV maximum		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

recording frequencies. Research results indicate that peak values can be related to forest road damage only with 10 Hz vibration frequency measurements. In that case, peak values represent the upper 20 % of values in the total data range.

Each measurement of the vibration total value is associated with the GPS coordinate of the measuring point, and the data are plotted on the map of the forest area using the ArcGIS 9.3 computer program.

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

Since the vibration total values range from 6.6 m/s^2 to 13.2 m/s^2 at 10 Hz readings, the values from the upper third of the data range, i.e. all vibration total values greater than 12 m/s^2, are displayed for further consideration (Figure 3.c). A grouping of values in two sets around an approximate position of impact holes on the forest road can be noted. However, It is impossible to precisely determine the location of road damage due to deviation of GPS coordinates of the measured points from the forest road route.

The next step is to display measured data for the vibration total values greater than 12 m/s^2, i.e. the peak vibration values (Figure 3C). In the above-mentioned total data range, the vibration total values from 12 m/s^2 up to a maximum of 13.2 m/s^2 represent the top 20 % of the measured data range.

In comparison with previous presentations, there is now a much more visible grouping of data at the points of damage to the forest road segment. At the same time, the greater the damage (larger pothole dimension), 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 a vehicle's movement along

Figure 3. Vibration total values on forest road segments

the same forest road segment, was determined as follows. At each vehicle passing, one of the variables was changed, for example, with 2 bar tyre inflation pressure the initial driving speed was 20 km/h, then 40 km/h and, ultimately, 60 km/h. The procedure was repeated after increasing the tyre inflation pressure to 2.5 bars or to 3 bars. The recording frequency was 10 Hz.

Table 3 shows average vibration total values and standard deviations for various experiments as related to the tyre inflation pressure and vehicle driving speed.
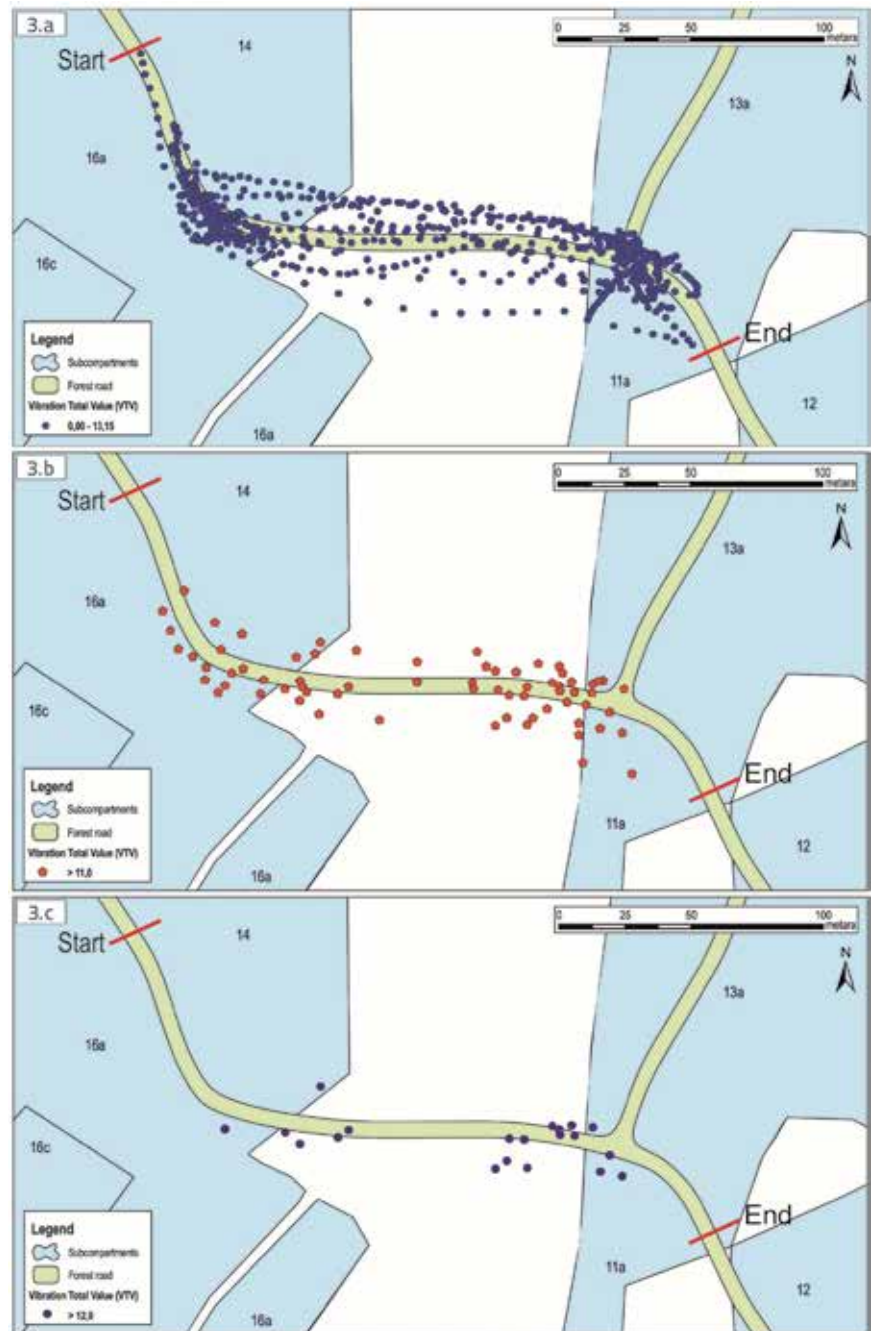
It can be noticed that all values increase with an increase in driving speed and tyre inflation pressure. The reasons for that lie in the fact that higher vibrations of the vehicle structure occur at higher driving speeds and are transmitted to the measuring device. At a lower tyre inflation pressure of 2 bars, the tyre is "softer" and it absorbs vibrations of the forest road better, and so the vibrations caused by road damage cannot be determined with sufficient accuracy. With "harder", 3-bar tyre inflation pressure, the vibration total value increases as a result of tyre adhesion loss.

Table 3. Statistical data of measured vibration total values at various 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

The above-presented results show that condition of forest roads can be estimated by means of vibrations. Vibration values depend on the speed of the vehicle and tyre inflation pressure. This is somewhat in line with the findings of Douangphachanh and Oneyama [11] who conclude that vibration records are greatly influenced by the speed of the test vehicle, the type of the vehicle, and the type of vibration measuring device. In addition, Gillespie et al. [23] and Sayers et al. [24] state that 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 various driving speeds and various 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 the tyre inflation pressure of 2 bars.

Zhao [25] reports that the vehicle speed ranging from 25 km/h to 90 km/h can be applied for measuring road roughness with axle accelerometers on urban roads. Jost [26] performed measurements of road roughness on 49 test sites on different roads with test speeds of 20, 32, 50, and 80 km/h. However, he used the smallest speed of 20 km/h on 12 test sites along earth roads as well as on 12 test sites on gravel roads. The measurements were recorded on 320 meters long road sections.

Based on the above mentioned research and data recorded at different speeds, it can be concluded that the most favourable vehicle speed for measuring the macadam forest road damage by accelerometer is 20 km/h.

Furthermore, when measuring road profile, many authors conclude that the tyre inflation pressure should be set according to manufacturer's recommendations, regardless of the type of vehicle, and that the tyre inflation pressure should be reduced when making measurements on gravel roads. According to Gillespie et all [23], when measuring the road pavement profile, the tyre inflation pressure must be set at the pressure recommended by the manufacturer to obtain the best measurement accuracy. When the tyre pressure is not near the optimum level as set by the manufacturer, the wheel to road contact pressure becomes more difficult to predict [27]. Lower tyre pressures have been found to increase traction and braking capabilities on uneven roads [28].

Since 1991, Croatian forestry has been using the Forest District Management System, a complex method that is being implemented by a single state-owned company Croatian Forests Ltd. Zagreb. Forest district is a predefined forest area in which forestry engineers conduct all planned activities in accordance with forest management plans, taking full responsibility for the realisation of such plans [29].

This implies frequent, almost daily, departure of engineers to the forest district for which they are responsible. In this case, an all-terrain vehicle is used for driving on forest roads. The vehicle the most commonly used by the Croatian Forests is Lada Niva, although today other vehicles are also used, but with similar dimensions and masses. The method for assessing forest road condition involving the use of an accelerometer-equipped vehicle is appropriate for collecting data when executing daily forest management duties, and the measurements do not imply any additional costs. At the same time, the road pavement information obtained in this way can be used by forestry experts as a basis for planning forest maintenance activities and for scheduling required investments.

Some measurement errors were detected when measuring vibrations with an Android application, as well as during data processing. The biggest problem is the GPS accuracy because the data collection depends mostly on the quality of the GPS signal. Although a satisfactory number of satellites was registered during measurements (5 to 6 satellites), large deviations of coordinates from the forest road route were observed. It should also be noted that the research was carried out during the vegetation period when tree crowns along the forest road also greatly affect the vehicle position measuring accuracy.

Another error in the Android application was detected with regard to the driving speed and travelled distance. Since the travelled distance and driving speed are recalculated using GPS coordinates, the inaccuracies similar to the previously described ones were registered. Therefore, the travelled distance and driving speed were measured and displayed on the basis of the data obtained from the vehicle.

The newly developed Android application also measures longitudinal slope of the forest road between two measuring points. Since this research was conducted on flat terrain, it was not possible to estimate validity of the data on the longitudinal slope of the road forest. Therefore, a research should also be conducted on an uneven terrain, and on a forest road presenting longitudinal inclination. It can however be assumed that measurement error is highly likely to occur, as computer calculation of longitudinal inclination is based on the coordinates of measuring points.

Errors also occurred due to an inadequate data recording format. The format used is not appropriate when performing data analysis. The quantity 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 that unrealistic results can be avoided. For these reasons the following action should be taken to improve the application:

- Use a more accurate GPS device, or carry out field measurements during the winter period when tree crowns will not disturb the measurements.
- Eliminate errors resulting from an inadequate data recording format.
- Enable application user to independently choose the beginning and end of the recording sequence, instead of the current automatic start of measurements as soon as the device is connected to satellite locations.
- Enable user to select a recording frequency.
- Remove route and slope data from the application, as unrealistic data is recorded; the size of files will thus also be reduced, which will additionally simplify data analysis.

5. Conclusions

The condition of forest road structures can be evaluated by vibration measurements using a simple and inexpensive data collection method. Due to the way forests are managed in Croatia, and considering the frequent passage of vehicles along forest roads, the assessment of the forest road pavement condition based on vibration measurements can be regarded as a simple and inexpensive way for collecting data.

According to the analysis of influence exerted by various recording frequencies, driving speeds and tyre inflation pressures on the vibration total value, the recording frequency of 10 Hz, vehicle speed of 20 km/h, and tyre inflation pressure of 2 bars, are recommended for estimating condition of forest roads. However, further development of the vibration-based assessment method should focus on the impact of different types of vehicles on measurement accuracy. Furthermore, the impact of various smart phone types on vibration values should also be studied, and an optimal sample size (length of forest road segment) should be determined.

The attention should also be drawn to some errors and shortcomings that were observed during measurements, such as problems with GPS accuracy, and use of Android application when recording data other than vibration (slope and route distance measurements). The data collection depends mostly on the quality of the GPS signal. It is recommended to perform measurements outside of the vegetation period when the quality of GPS signal is less influenced by tree crowns. The authors believe that the new method will provide a consistent and unbiased approach to ranking investments in the maintenance of the primary forest transport infrastructure, and that it will constitute an appropriate tool for determining sustainability of forest road maintenance activities.

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