JOURNAL OF FOREST SCIENCE, *63*, 2017 (8): 363–369

doi: 10.17221/43/2017-JFS

Research on forest terrain roughness as a source of dynamic action on the vehicle

Milan MIKLEŠ, Milan HELEXA, Juraj MIKLEŠ*

Department of Environmental and Forestry Machinery, Faculty of Environmental and Manufacturing Technology, Technical University in Zvolen, Zvolen, Slovak Republic

**Corresponding author: milan.helexa@tuzvo.sk*

Abstract

Mikleš M., Helexa M., Mikleš J. (2017): Research on forest terrain roughness as a source of dynamic action on the vehicle. J. For. Sci., 63: 363–369.

The issue of terrain conditions is very complex and its description is approached from different perspectives and with different objectives. Because it consists of the gathering of basic information for a mobile object, a wheeled forestry tractor, the terrain-vehicle approach was taken as the basis. Ground conditions are part of the operating conditions of wheeled forestry tractors. Uneven ground can be regarded as a source of vibration in the vehicle – towing truck. In this respect, given the random shape of the surface roughness, the solution to vibrations leads to a terrain correlation analysis in order to obtain a correlation function and power spectral density of the ground surface. Scanning of the ground micro-profile was performed using a device for quick terrain scanning, which from the mechanical aspect consists of a towing vehicle and a measuring carriage. Correlation function and power spectral density are the evaluation based on ground micro-profile measurements and the results of calculations. Measurements of forest terrain (road) micro-profile were done in the area of Little Fatra and Little Carpathians in Slovakia. In geological terms, the measurements were done in an area with the occurrence of gneiss, granite, limestone and flysch. No measurements were performed in a sandy area.

Keywords: forest soils; micro-profile; correlation analysis; power spectral density; wheeled forestry tractor

There are many approaches to the morphological description. It is the simplest approach, from the measuring and evaluating slope angles and creating their statistics weighted average according to the area they occupy (Imine, Fridman 2008), through the division of surface shape into macro- and micro-relief, as well as meso- and mega-relief (González et al. 2008), to terrain classification based on semi-quantitative relationships (Davis, Thompson 2001; Barbosa 2012). This schematic approach further leads to terrain quantification using geomorphological parameters such as hypsometric integral, slope curvature, grain, field exposure. Quantification is processed in a statistical form (probabilistic model). Other factors such as vegetation, hydrography, civilization factor, etc., are also considered.

The most investigated are the problems in the area of terrain roughness and physical properties of soil. Bekker (1983) provided an assessment of the interaction between surface geometry and the geometry of the mechanical vehicle properties in terms of obstacle-transportation perspectives, vehicle driving and ride comfort. In terms of vibration, Bekker (1983) observed terrain irregularities as a source of the vehicle vibration. In this respect, given the random shape of the surface roughness, the solution of vibrations leads to terrain correlation analysis in order to obtain a correlation function and power spectral density of the terrain surface. In reality, it is the discrete-time Fourier transform. If we mark the distance, i.e. the independent variable of roughness using "x" and the height of roughness using "$h(x)$," the time of transformation $x = v \times t$, we get the function of the roughness height $f(t)$.

In the case of random processes, $f(t)$ is a random function. We compile a characteristic feature for it in the form of an autocorrelation function (Eq. 1):

$$R(t_1, t_2) = E\left\{\left[f(t_1) - m(t_1)\right] \times \left[f(t_2) - m(t_2)\right]\right\} \quad (1)$$

where:

E – operator denoting the averaging across all process implementations in the indicated parameter values,

$m(t)$ – mean.

It is understood that $m(t) = E[f(t)]$. If $R(t_1, t_2) = R(t_1 + h, t_2 + h)$ for all h, it is true that $R(t_1, t_2) = R(\tau)$ while $\tau = t_2 - t_1$. This means that it is a stationary process. Then, according to the Wiener-Khinchin theorem, it applies Eqs 2 and 3. Eq. 2 expresses the inverse Fourier transform, Eq. 3 expresses the direct Fourier transform:

$$R(\tau) = \int_{-\infty}^{\infty} \exp(i\omega\tau) S(\omega) d\omega \quad (2)$$

where:

$R(\tau)$ – autocorrelation function,

$S(\omega)$ – power spectral density.

$$S(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \exp(-i\omega\tau) R(\tau) d\tau \quad (3)$$

According to Wiener, this procedure is a "generalized shape of harmonic analysis" for non-periodic functions that have "consistent" properties for $t \to \infty$.

The previously mentioned knowledge implies the need to subordinate terrain categorization not only to the final destination, but also to the means by which the information is gathered. In terms of throughput we can divide the roughness and barriers to passable and impassable. Passable roughness can be measured by a mobile device along the route which the studied object passed across (Udas 2011; Thomsen et al. 2015). Impassable barrier needs to be examined in specific ways.

The present research was mainly focused on obtaining the statistical characteristics of forest terrain roughness (mainly forest roads) marked as micro-roughness (micro-profile) with a height up to 30 cm. The obtained statistical characteristics, in particular the power spectral density, can be used in many areas of the mobile forestry equipment design, especially wheeled forestry tractors which the research was primarily focused on. Information on the power spectral density of the terrain micro-roughness can be used e.g. for the calculations of the life of supporting structures and frames, as well as when assessing the vibration level of wheeled forestry tractors. However, it can also be used in assessing their driving characteristics.

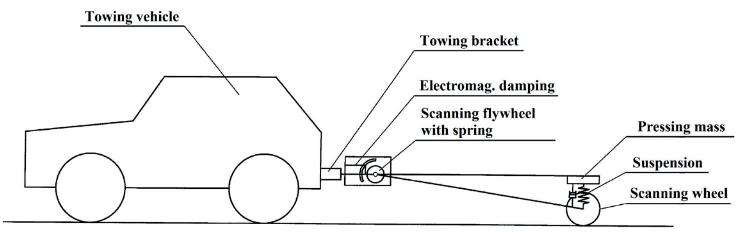
MATERIAL AND METHODS

Micro-profile scanning was done using a device developed in the Research and Development Institute of the Heavy Engineering Plant in Martin. From the mechanical perspective, the device for quick terrain scanning consists of a towing vehicle and a measuring carriage. As a towing vehicle to measure forest roads, we chose a GAZ off-road vehicle (Gorky Automobile Plant, Russia) with a reduction to achieve a slow, steady motion.

The measuring carriage is connected with the towing vehicle using an articulated joint. The measuring carriage has one wheel attached at the end of the fork. To prevent the wheel from jumping aside when moving in the terrain, it is pushed using a weight on a spring and damper. We attached the weight on the fork and the joint in a way that the properties of the spring and damper do not impact the measurement accuracy. The fork movement is transmitted to a pendulum – it is a flywheel on two ball bearings. It is brought to the central position by a spring. The flywheel has an arm with an aluminium segment moving in the narrow gap of the electromagnet poles. Eddy currents generated in the segment cause damping of its movement. An arm to transmitting the motion to a sensor is attached to the balance lever pin. The arm rotates around its axis in the sensor and reduces the measured angle in relation to the length to the balance lever axis and length to the sensor coil. The angle of the pendulum (up to 30°) is reduced about 50 times in the sensor. Then we can regard this movement of coils in the sensor, which is a relative movement of the coils in the sensor, as linear. The drawing of the measuring device with the towing vehicle is shown in Fig. 1a, the towing vehicle itself from the measuring device during measurement in Fig. 1b.

The angle of the pendulum during the measurement is reduced by mechanical transmission and converted to an electrical signal using an inductive sensor. Carrier current with a frequency of 5 kHz is supplied to the inductive sensor, and an amplitude modulated signal proportionate to the distribution is located at the output of the inductive sensor. The signal is amplified, and guided in the rectifier which recognizes the phase. After filtration of the current components corresponding to the carrier frequency, the signal is fed to the width modulator.

(a)



(b)

Fig. 1. System of towing vehicle – measuring truck for the measurement of the terrain micro-profile: diagram of the measuring device (a), terrain measurements (b)

This modified signal is recorded on a Quantum X MX 840 A recording equipment (HBM, Germany). The recorded signal must be further adjusted for additional processing. The given adjustment was performed in Catman Professional software (Version 5.0, 2005). The adjustment consists mainly of demodulation of recorded signals and filtering of higher frequencies.

The micro-profile measurement is carried out at the speed of 2 $m \cdot s^{-1}$. Sampling frequency is 20 Hz, corresponding to the sampling length of 0.1 m. In terms of the "Shannon-Kotelnik" criteria, useful information can be taken for 2.5 times of the sampling step, which is 0.25 m. Since we demarcated the micro-profile for wheeled forestry tractors at a lower limit of 0.5 m, the obtained information is credible. Constancy in a recorded value is checked by *t*-test at a significance level $\alpha = 0.005$, constancy in variance is checked by *F*-test at a significance level $\alpha = 0.001$. Approximation using a straight is applied to compensate (eliminate) the trend in mean value. Ormsby digital filter was used to filter the recorded signal. The result of the calculations is the correlation function and power spectral density.

RESULTS

We measured the micro-profile in a total of 31 stretches of forest roads. After removing clearly non-stationary and false measurements, we selected 21 sections from this number, which we evaluated. Forest terrain (road) micro-profile measurements were done in the area of Little Fatra and Little Carpathians in Slovakia. In geological terms, the measurements were performed in areas with the occurrence of gneiss, granite, limestone and flysch. No measurements were performed in sandy areas. We carried out measurements on selected forest road grades 1L, 2L, and hauling road, third class (3L) defined according to the standard STN 73 6108 Forest Transport Network. Fig. 2 shows examples of roads of individual classes on which the measurements were done. The measurements were performed during the summer months in dry weather. The surface of the forest roads was dry (asphalt or stone surfaces). For ground surfaces, the surface was dry to slightly wet, but on some stretches of roads we also encountered a wetter environment, especially on 3L roads in the wooded sections. The road surface was not mechanically modified prior to the measurement, so the natural profile of the road was detected as it was found at the site. Depending on the size of the standard deviation and shape of the power specific density, we divided the results into four classes:

(*i*) 1a and 1b class (roughly equivalent to class 1L forest roads): $2 \times S_h$ up to about 10 cm;

(*ii*) 2nd class (roughly equivalent to class 2L forest roads): $2 \times S_h$ up to about 20 cm;

(*iii*) 3rd class (roughly corresponds to 3L class forest roads): $2 \times S_h$ up to about 30 cm.

At the same value of twice the standard deviation of the roughness height ($2 \times S_h$), classes 1a and 1b differ in the shape of power spectral density. Class 1a roughly corresponds to asphalt forest roads and class 1b to roads with the reinforced stone surface. Figs 3a–d show partial typical power spectral densities (in particular based on the shape – the frequency content), representing classes 1a, 1b, 2 and 3 of roughness profiles in forest terrain and roads.

Experimental results for further calculations approximated by a system of four (in the third class of five) exponentials are as follows, Eq. 4:

$$S_i(\omega) = a_i \times 10^{b_i \times \log\omega_i} \left(\mathrm{m^3 \cdot rad^{-1}}\right) \quad (4)$$

where:

a_i, b_i – approximation coefficients,

ω_i – frequency ($\mathrm{rad \cdot m^{-1}}$).

Table 1 summarizes the distribution of measured terrain distances based on road and micro-profile classes and it is determined by the absolute and relative frequency of occurrence of terrains based

Fig. 2. Examples of forest road surfaces for which measurements were performed: class 1L forest road – class 1a (a), class 1L forest road – class 1b (b), class 2L forest road (c), class 3L forest road (d)

on classes in the examined group of 21 results. For further use, until a larger set of results is obtained, we propose to consider the probability of occurring micro-profiles of forest terrain and road types based on the relative frequency of occurrence in Table 1. The calculated coefficients of the exponentials together with the frequency band of approximation validity are given in Table 2.

DISCUSSION

Temporal stability (volatility) of the information should be examined when assessing the possibility of transmission of information about the terrain micro-profile (Bendat, Piersol 1967). The micro-profile of forest roads is exposed to various natural and technical factors over time. In particular the movement of the vehicles must be considered to be a technical impact. Concerning the natural conditions (geological origin, humidity, etc.), it can be assumed that they do not substantially alter over time and therefore have no importance when considering the transmission of information to another machine. If we assume that a new (another) vehicle will not have substantially different frequency characteristics from the preceding vehicle, it is not needed to expect a difference in its impact on the terrain micro-profile either. The temporal action of the vehicle on the terrain does not substantially alter.

Facts decisive for the possibility of transmitting information about the terrain micro-profile are technological conditions of the proposed machine's activity and the area of information utilization. Minor technological changes (small changes in load and speed) induce smaller changes of the terrain micro-profile impact on the vehicle, especially because the frequency relations of the terrain micro-profile and the vehicle are not substantially altered (Svenson, Fjeld 2014). Conversely, in the case of more substantial changes in speed and load, the impact of the micro-profile as one of the external load components can significantly change. In terms of the utilization of information on the terrain micro-profile, there will be a difference when considering the micro-profile impact on the vibra-

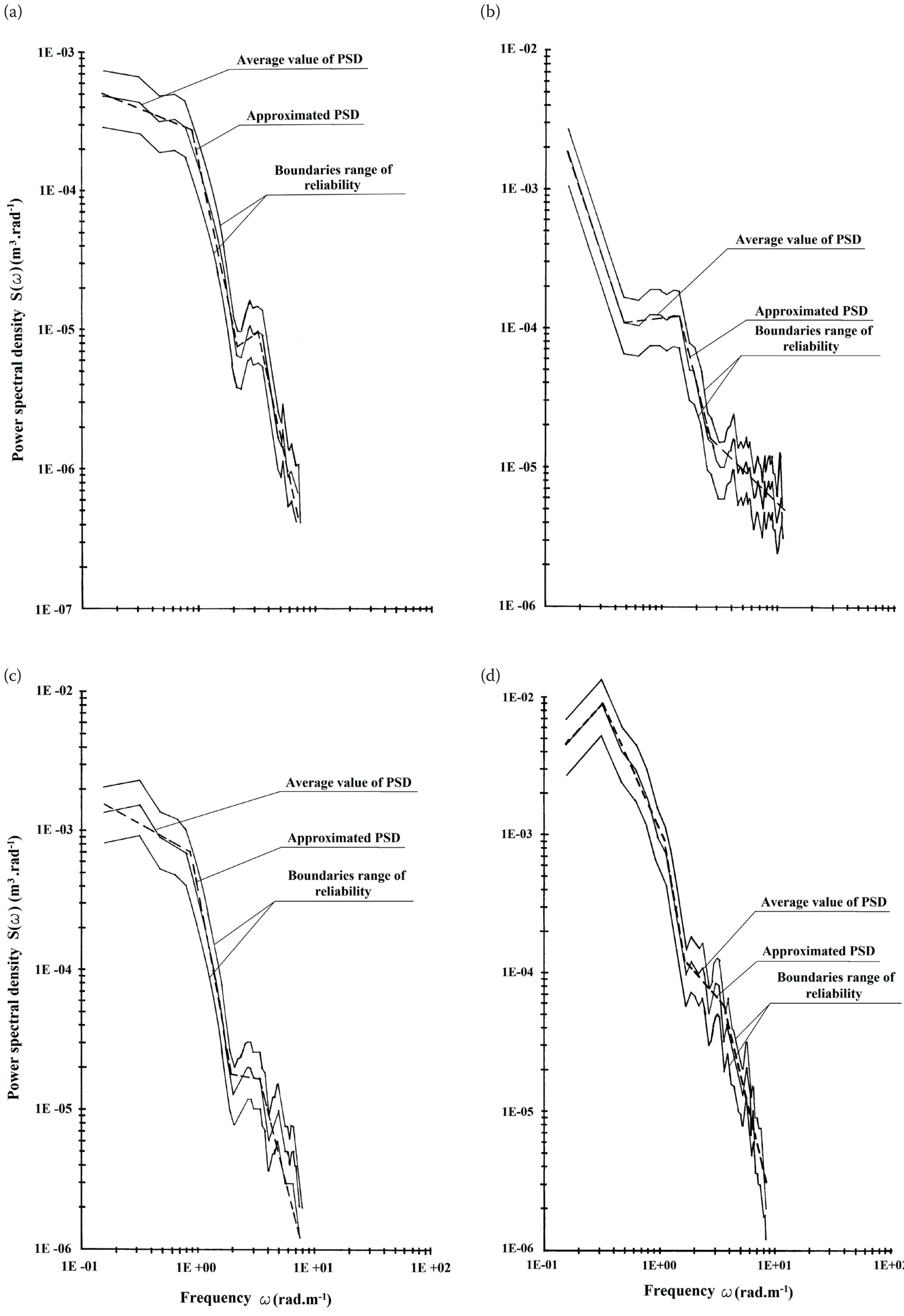


Fig. 3. Comparison of approximated power spectral density (PSD) of 1a (a), 1b (b), 2nd (c), 3rd (d) class with respect to the mean PSD in the class, confidence zone at a significance level of 0.99

Table 1. Distribution of measured terrain sections according to the type of road and micro-profile class

Road class	Haul		Sloping		Skid
	amount	(%)	amount	(%)	amount
1a	6	60	4	50	0
1b	2	20	0	0	1
2	2	20	2	25	2
3	0	0	2	25	0
Total	10	100	8	100	3

The relative amount (%) was not evaluated for skid trails

tion of the vehicle and its parts, when considering the load of the vehicle and its parts, when considering the vehicle noise, etc. Problems can sometimes be solved based on simple consideration of measurements, sometimes only by detailed monitoring of the whole machine or its parts.

For a technologically similar machine used in technologically similar conditions, it could be foreseen that the information on the effect of the terrain micro-profile can be transferred to a new machine without problems (Fassbender et al. 1997). For the machine that is significantly technologically different from the previous one, or is used in significantly different technological conditions, it is necessary to explore the transmission of information on the terrain micro-profile operation in more detail (to examine the area of information utilization and to define new boundary conditions).

For machines whose wheelbase is greater than 2 m, the stochastic dependence of actuating the successive axles (Sugjoon 2003) can be neglected. In other words, in terms of the drive force relation to the surface roughness, successive axles may be considered stochastically independent. Transmission of micro-profile information is independent of the vehicle dimensions in these circumstances.

CONCLUSIONS

We believe that in terms of the shape of power spectral density of the terrain micro-profile, no new forms beyond those measured are to be expected in Slovakia (except for the area of sands – Záhorie). This view is supported by the fact that the trend is simplified by approximation of the power spectral density of the terrain micro-profile according to Bekker (1969) and Wong (1989) and fluctuates in a narrow range of values. It is not a reason for the above considerations to be invalid for forest roads in Slovakia as well. Representation of individual micro-profile classes may differ by region. Higher

Table 2. A summary of exponential characteristics approximating the power spectral density for individual sections

Class	a_1	b_1	ω_1 (rad·m^{-1})	a_2	b_2	ω_2 (rad·m^{-1})	a_3	b_3	ω_3 (rad·m^{-1})	a_4	b_4	ω_4 (rad·m^{-1})	a_5	b_5	ω_5 (rad·m^{-1})
1a	2.7095×10^{-4}	0.3287	0.8	1.8467×10^{-4}	4.0086	2.3	4.0357×10^{-6}	−0.7577	3.4	8.5923×10^{-4}	3.7456	7.8	–	–	–
1b	1.6613×10^{-5}	2.5258	0.5	1.1938×10^{-4}	−0.1238	1.4	2.9546×10^{-4}	2.9291	3.4	3.6375×10^{-5}	0.8118	11.0	–	–	–
2	6.5738×10^{-4}	0.4758	0.8	3.7055×10^{-4}	4.4150	2.2	2.0558×10^{-5}	0.1819	3.6	3.0193×10^{-4}	2.3707	11.8	–	–	–
3	2.6427×10^{-2}	0.9536	0.3	1.0639×10^{-3}	1.8672	1.1	1.4405×10^{-3}	4.8160	1.8	1.2040×10^{-3}	2.7135	3.4	3.6900×10^{-3}	3.3290	8.6

confidence interval < ω_{i-1}, ω_i), ω_0 = 0.16 rad·m^{-1} for all classes representation of "better" roads is given both by older geological age of the surface and better state of the forest road network. But different representation of the individual classes can also be expected in the particular regions.

The micro-profile of skid trails, which should be paid attention next time, will consist of natural geological and possibly technological conditions (stumps, branches, trunks) and will affect far more than the micro-profile of terrain, as was the case for the micro-profile of forest roads. Monitoring the micro-profile of skid trails or rough terrain is technically and theoretically much more difficult (ground clearance of a towing vehicle, small lengths of the measured sections, strong non-stationarities).

References

Barbosa R.S. (2012): Vehicle vibration response subjected to longwave measured pavement irregularity. Journal of Mechanical Engineering and Automation, 2: 17–24.

Bekker M.G. (1969): Introduction to Terrain-vehicle Systems. Ann Arbor, University of Michigan Press: 580.

Bekker M.G. (1983): Prediction of Design and Performance Parameters in Agro-forestry Vehicles: Methods, Tests, and Numerical Examples. Ottawa, National Research Council of Canada: 232.

Bendat J.S., Piersol A.G. (1967): Measurement and Analysis of Random Data. New York, John Wiley & Sons, Inc.: 390.

Davis B.R., Thompson A.G. (2001): Power spectral density of road profiles. Vehicle System Dynamics, 35: 409–415.

Fassbender F.R., Fervers C.W., Harnisch C. (1997): Approaches to predict the vehicle dynamics on soft soil. Vehicle System Dynamics, 27: 173–188.

González A., O'Brien E.J., Li Y., Cashell K. (2008): The use of vehicle acceleration measurements to estimate road roughness. Vehicle System Dynamics, 46: 483–499.

Imine H., Fridman L. (2008): Road profile estimation in heavy vehicle dynamics simulation. International Journal of Vehicle Design, 47: 234–249.

Sugjoon Y. (2003): A study on terrain-surface modeling and searching algorithms for real-time simulation of off-road vehicles. Vehicle System Dynamics, 39: 353–363.

Svenson G., Fjeld D. (2014): The impact of road geometry and surface roughness on fuel consumption for Swedish logging trucks. In: Philips S. (ed.): Proceedings of the 5th Transport Research Arena, Paris, Apr 14–17, 2014: 1–10.

Thomsen L.M., Baartman J.E.M., Barneveld R.J., Starkloff T., Stolte J. (2015): Soil surface roughness: Comparing old and new measuring methods and application in a soil erosion model. Soil, 1: 399–410.

Udas A. (2011): Road variability and its effect on vehicle dynamics simulation. [Ph.D. Thesis.] Iowa City, University of Iowa: 210.

Wong J.Y. (1989): Terramechanics and Off-road Vehicles. Amsterdam, Elsevier: 251.

Received for publication March 15, 2017
Accepted after corrections June 28, 2017