FORMEC 2010
Forest Engineering: Meeting the Needs of the Society and the Environment
July 11 – 14, 2010, Padova - Italy

MEASUREMENTR OF FOREST MICROTOPOGRAPHY
- AN APPROACH FOR OPTIMIZATION OF UNDERCARRIAGE OF THE FOREST VEHICLES UTILIZING MICROTOPOGRAPHY -

Takeshi Yamada, Toshiaki Endo

Forestry and Forest Products Research Institute
Matsunosato-1
Tsukuba-city, Japan
e-mail: kenchan@ffpri.affrc.go.jp

Keywords: forest machinery, forest vehicle, crawler, microtopography, mobility

Abstract: *Improved mobility for crawler vehicles on steep slopes and rough terrain depends on the ground contact area and the even distribution of ground contact pressure. Forest microtopography, assumed as the basis for undercarriage design of forest vehicles, was measured using a device that we developed. The measurement data was then used in an attempt to optimize the undercarriage specifications. The vehicle's ability to pass over rough terrain was determined by comparing its thrust force, which was derived from the ground contact ratio in the measured microtopography data, with the required thrust force calculated using a Microsoft Excel macro program. Fundamental specifications of the assumed vehicle and parameters of soil nature were input as constants and variables. Although the program determined the optimum undercarriage specifications, its validity is difficult to prove due to the lack of a verification method. Future tasks include improving the program and proving its validity.*

1. Introduction

Forest vehicles must be capable of tracing the forest-floor microtopography as precisely as possible while retaining sufficient mobility on rough terrain and causing a minimum of soil disturbance. Lower vehicle mobility results smaller working area. Soil disturbance reduces the productivity and public functions of a forest. To ensure that forest vehicles accurately trace the forest microtopography, the microtopographic properties must be identified and a vehicle undercarriage must be designed appropriately. However, available data on forest microtopography is very limited and there is no established measuring method. Consequently, we developed a microtopography measuring method and measurement device. There is abundant surface measuring technology such as laser 3D scanners and optical heterodyne scanners, but these non-contact devices cannot measure ground surface that is covered with plants. It is necessary to measure the profile of the ground that can support forest vehicles. We adopted a contact method to avoid measuring pseudo surfaces such as plant communities and slash piles. Various contact measurement methods have been reported such as the use of a multi-probe device for forest terrain profiles (Imatomi, 1984) and the use of wheel devices (Fukuda et al., 1984; Ohmiya and Matsui, 1982a). We developed a device with sufficient precision and resolution for microtopography measurement under the average ground contact pressure of ordinary forest vehicles. We used our device to obtain microtopographic data at 3 sites and then we built a simple program using this data to optimize the specifications for the undercarriage of forest vehicles.

2. Measuring device, method and test sites

2.1 Measuring device

The mechanism of the measuring device is described below and illustrated in Figure 1. The base part is an aluminum rail 7,680 mm in length that can be disassembled into four parts for portability. Precise alignment is achieved by adjustable supports guided by laser beam. The stage, formed by aluminum slides on the rail, is stopped at intervals of 30 mm by means of a click catch and screw holes. A magnetic displacement sensor slides on the stage perpendicularly to the rail as a height sensing probe. Batteries and a data logger are equipped on the stage. The probe measures the height of the ground surface at every temporal stop position. Since the probe output is analogue voltage, measurement precision depends on the resolution of the data logger, which is approximately 0.25 mm. The measurement displacement range for the sensor is 1000 mm. To design the vehicle's undercarriage utilizing the measured data, measurement must be conducted applying the ground contact pressure of the real vehicle. A pressure sensor consisting of a magnet, a magnetic switch and a spring was added at the bottom of the probe (Figure 1). The height of the terrain was measured under pressure of 50kPa (approximately average ground contact pressure of typical forest vehicles) and recorded to a data logger. Height data was measured at intervals of 30 mm on

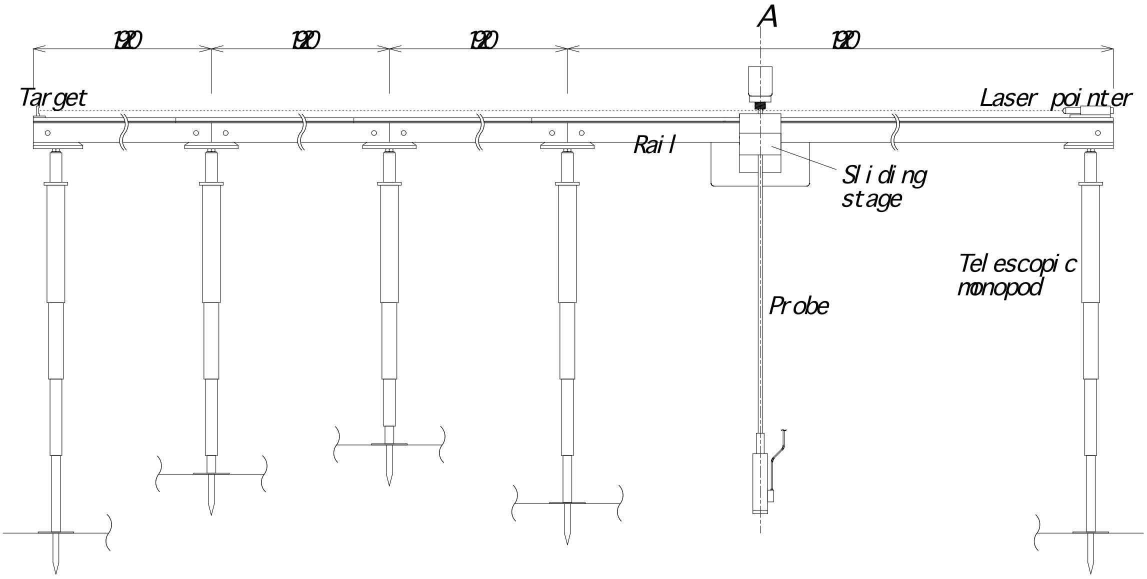


Figure 1a. Developed forest microtopography measuring device

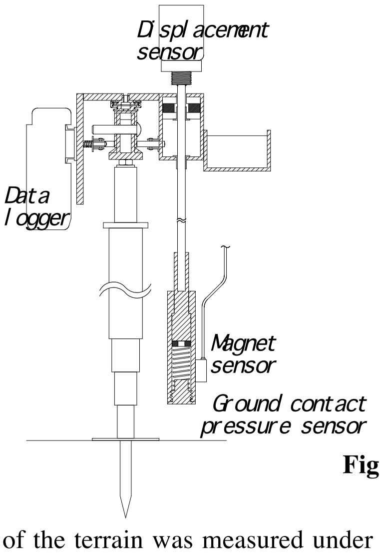
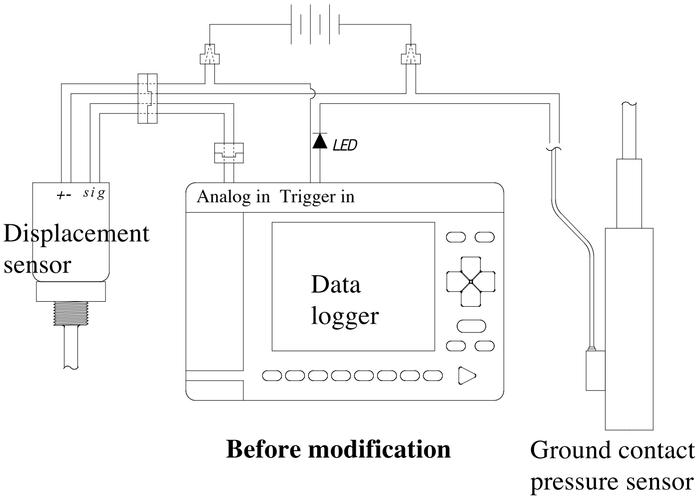
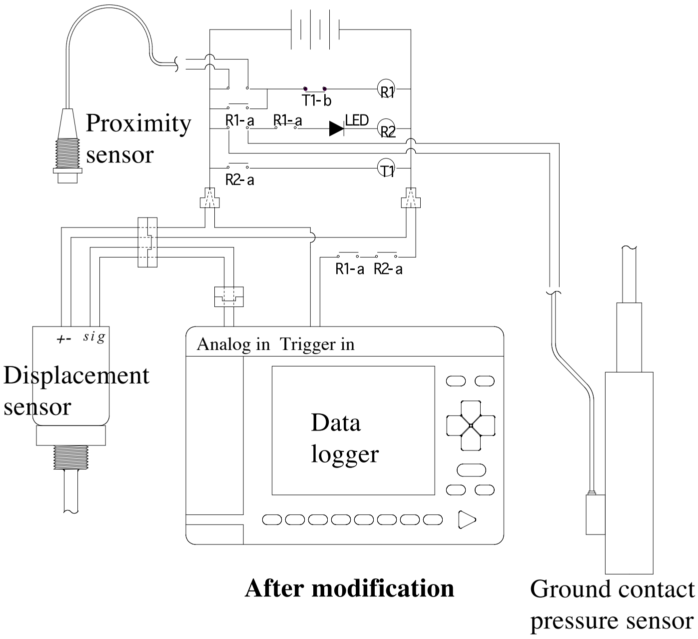


Figure 1b. Macrographof cross section at A

a straight line. The rail was always set in the direction of the fall line, which is assumed to coincide with the longitudinal direction of a vehicle driving on sloped terrain. According to the purpose of this study, measurement was conducted on slopes having a slant angle of less than 30 degrees.



Before modification



After modification

Figure 2. Circuit of measuring device

Preliminary measurement identified a problem with duplex measurement on one point. The device often took a primary measurement of the litter layer surface, and then a secondary measurement of the mineral soil surface after penetration through the litter layer. Thus, signals from the pressure sensor were generated for both surfaces. To prevent this problem, we equipped the device with a circuit consisting of a sensor and relays (Figure 2). The circuit fell into an excited state only once when a proximity sensor passed above the magnetic metal plates set on the rail at every 30 mm. Then it returned to the basal state by a signal from the pressure sensor. The height data was recorded only during the excited state of this circuit, which responds only to the first signal from the pressure sensor. A LED indicator on the circuit displays the state of the circuit.

2.2 Test sites

We measured the microtopography of 28 plots at 3 test sites: Nanakai Test Site, Tsukuba Test Site and Tengakura Test Site. The measured plots were classified into 5 categories: natural forest, plantation forest, afforestation area, harvested area and logging road. The natural forest consisted of broadleaf species. The plantation forest consisted of planted Japanese cedars (*Cryptomeria japonica*). The afforestation area had been treated with stripe site preparation. Limbs, tops and slashes were piled in stripes along contours, and Japanese cedar seedlings were planted between stripes one year before measurement. The harvested area was covered with heavy vegetation due to long-term abandonment and was strewn with slashes. The logging roads had been constructed for crawler tractors at the top of a ridge and hillside. As vegetation had not yet recovered due to soil compaction, soil was exposed on the entire surface and was slightly eroded. The number of the measuring plots were 2 of harvested area, 4 of afforestation area, 11 of natural forest, 6 of plantation forest and 5 of logging road. All measurements were conducted during winter to avoid difficulties caused by vegetation.

3. Result of measurement

Height data totaled 257 items with 256 intervals, obtained by measuring each site plot. A profile of the microtopography was constructed by connecting the data. Total profile line length could be used as the microtopography roughness index. When the data was thinned and every two data items were connected, a profile was observed at intervals of 60 mm. By repeating this thinning process, a profile at intervals of 30×2^n ($n = 0$ to 8) mm could be obtained. This is considered to be one method of coarse graining. We named the value of these exponentially increasing intervals "scale length". The total profile length decreases and the profile smoothes out with the scale length (Figure 3).

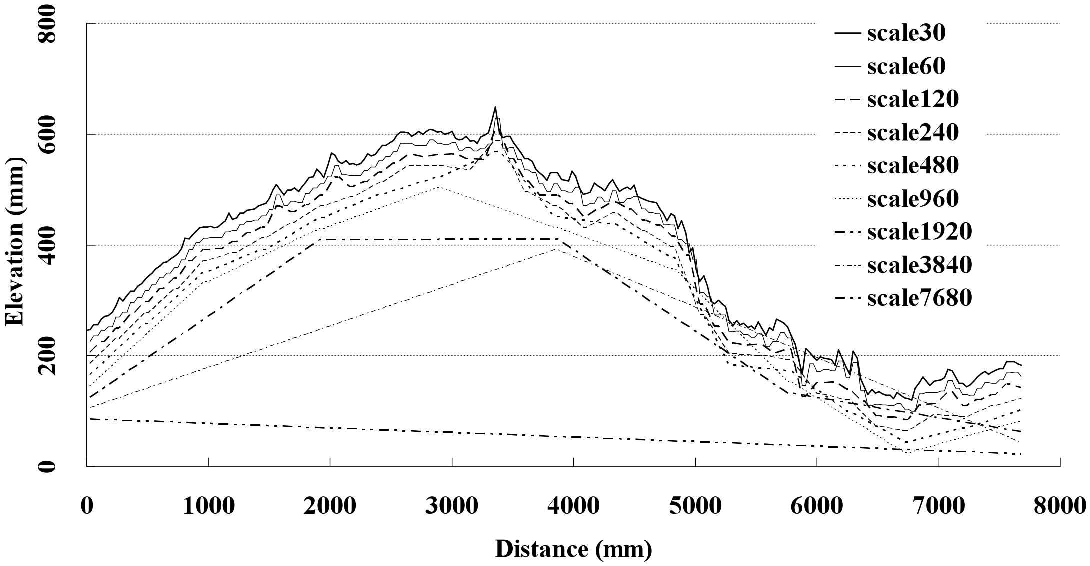


Figure 3. Method of coarse graining

The most common method used to analyze forest microtopography is power spectrum analysis (Bekker, 1969 ; Imatomi, 1984 ; ISO, 1995 ; Ohmiya and Matsui, 1982b). The power spectral density for the roughest (Nanakai harvested area 2, NHA2) and the smoothest (Nanakai logging road 1, NLR1) microtopography in this study is shown in Figure 4. The coefficient and exponential of the regression curve for NHA2 are $10^{3.82}$ and -1.65, those of NLR1 are $10^{1.26}$ and -2.17, respectively. According to the ISO 8608 road profile classification, NHA2 is Class H and NLR1 is Class G (ISO, 1995; Lombaert et al., 1999; Ohmiya and Matsui, 1986). It is considered that the roughest forest terrain is not passable by an ordinary vehicle, and that even the smoothest forest terrain is much rougher than a "very poor" road according to former classification.

Figure 5 indicates the average total length of each category. Total profile length could be used as a microtopography roughness index for each scale length. Also, the maximum slant angle (absolute value) of the profile line decreases according to corresponding scale length. Figure 6 indicates the average maximum slant angle for each category, which shows a similar tendency as that for total length. The categories were sorted in descending order for roughness testing significance of difference of both total profile length and maximum slant angle at small scale length between categories by t-test: harvested area > afforestation area ≥ natural forest = plantation forest > logging road. The results of t-test are shown in Table 1. At large scale length, the difference between categories becomes obscure. The measurement was done only once at one place because the measurement was conducted destructively compacting soil surface by contact pressure.

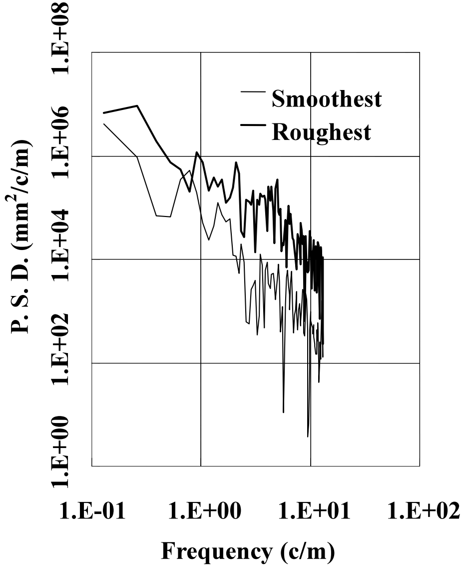


Figure 4. Power spectrum density of the roughest and the smoothest microtopography

If the forest microtopography displays self-similarity such as fractal profile, the total profile length must align linearly with the scale length on a logarithmic scale. In fact, it lines up concavely, which means that the frequency of small-scale roughness is higher than that of large-scale roughness. We decided that the microtopography does not have self-similarity. Actually, small-scale roughness of the ground surface depends on the density of matter such as limbs, tops, slashes, vegetation and tree roots. The original topography seems to influence only larger-scale roughness.

Table 1. Results of t-test for difference of the population mean between categories

	L at 30	L at 60	S at 30	S at 60	**Total**
harvested area – afforestation area	=	>	>	>	>
afforestation area – natural forest	=	=	>	>	≥
natural forest – plantation forest	=	>	=	=	=
plantation forest – logging road	>	>	>	>	>

L means total length, **S** means maximum slant angle
at 30 and **at 60** mean at scale length 30 and 60 respectively
> means left is significantly larger than right, **=** means there is no significant difference
Significance level is **5%**, **Total** evaluation is decision majority

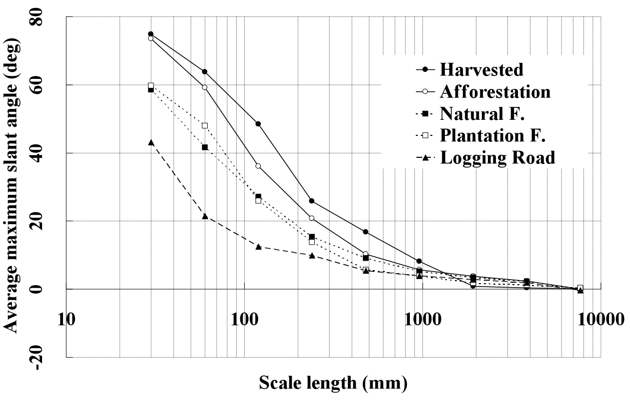


Figure 5. Average total profile length for each category

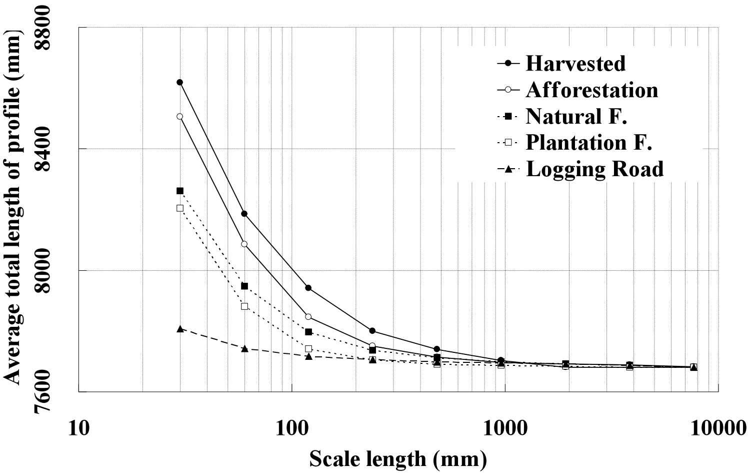


Figure 6 Average maximum slant angle for each category

4. Simulation method

We developed a computer program using the macro function of Microsoft Excel to optimize the specifications for the undercarriage of a forest vehicle. The program simulates the movement of a virtual vehicle model on the terrain given by the microtopography data, to determine whether the ground contact ratio of the crawler is sufficient for passage. The final output is the optimized specifications for a forest vehicle. This simulation is statically conducted. No dynamic factor is included.

4.1 Vehicle model

A crawler vehicle model with a very simple floating suspension system was assumed (Figure7). It has independent road wheels aligned at equal intervals, which move vertically and have the same suspension stroke and spring constant.

In order for the vehicle to successfully travel on varied terrain, it needs sufficient thrust force to climb a 30° slope having roughness equal to that of the roughest microtopography data collected in this study. Thrust force here means the total shear resistance of the soil under the contact area of the crawlers; it is not related to the driving force from engine power. In this program, variables change stepwise within a limited value range until all combinations of variables are completed, in order to determine if the vehicle model can travel on the terrain in the microtopography data.

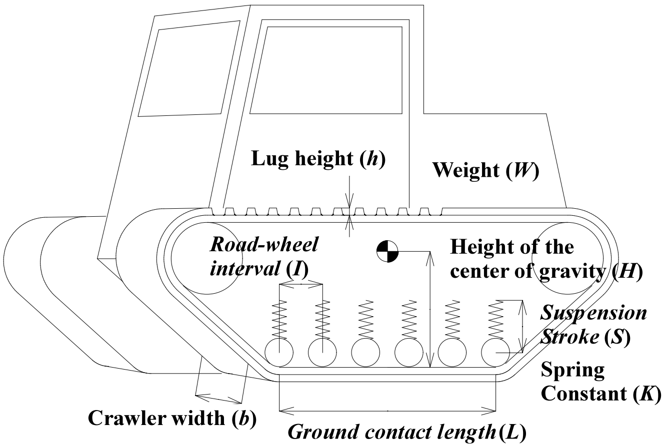


Figure 7. Vehicle model

4.2 Constants and variables

First, it was necessary to extract the constants and variables from the fundamental specifications to utilize for the program. Weight (W), height of the center of gravity (H), crawler width (b), crawler lug height (h), and the results from the box shear test on soil cohesion (c) and internal friction angle (ϕ) were required as constants, and ground contact length (L), road wheel interval (I) and suspension stroke (S)

were required as variables for processing (Figure 7). Variables would be examined and selected to optimize the specifications.

Formula (1) derived by Bekker (1960) was the basis for determination.

$$F = bLc\left(1+\frac{2h}{b}\right)+\frac{W}{2}\tan\varphi\left\{1+0.64\left[\frac{h}{b}\cot^{-1}\left(\frac{h}{b}\right)\right]\right\} \qquad (1)$$

where F is thrust force per crawler. Thrust force of the vehicle is 2 times by F. The required thrust force is derived from $W\sin\alpha$. Where α is the slant angle of the slope, it is fixed at $\pi/6$ (=30°) as explained above. Thrust force while the vehicle model is traveling on the terrain can be derived using Formula (1), multiplying L by the ground contact ratio of the crawler. Then, it is necessary to obtain the real value of the ground contact ratio. Ground contact ratio was defined as the number of road wheels contacting the ground divided by the total number of road wheels. Comparing the calculated thrust force on the roughest microtopography with the required thrust force, it was possible to determine whether the vehicle model could travel on sufficiently varied terrain.

The constants are temporarily decided as below. The size and weight of the vehicle was assumed realistically minimum value in which the vehicle has expected performance. Values of soil properties are measured value at Nanakai test site. Assumed constants were shown in Table 2.

Table 2. Fundamental specifications of the vehicle model

Weight (W)	2000 kg
Height of the center of gravity (H)	400 mm
Crawler width (b)	180 mm
Lug height (h)	30 mm
Cohesion of soil (c)	0.34 N/cm^2
Internal friction angle of soil (ϕ)	24.1° degrees

The range of variables defined before simulation is described below. Minimum ground contact length is $6\tan\alpha H$ under the condition that ground contact pressure must be loaded on entire length of the ground contact area of crawlers. Since it is loaded on the entire crawler length only while the center of gravity is at the middle third (center of trisected parts) of the crawler length (Sugiyama, 1972). Here, the center of gravity of the vehicle model is assumed to be the center of ground contact length on level land. A half of the middle third (1/6) of ground contact length must be larger than displacement of the center of gravity by slant angle. Maximum ground contact length is the value that limits ground contact pressure to higher than 25kPa. This is because 25kPa is as low as the ground contact pressure of crawler vehicles ordinarily used on poor ground; less than 25kPa requires too much ground contact length or crawler width, which degrades vehicle mobility on stable ground. Ground contact length (L) is rounded off to divisible value by intervals of road wheels (I) from more than the minimum value to less than the maximum value for calculation. The range of suspension stroke is determined to be 0 to 200 mm at intervals of 10 mm. Too much suspension stroke will make the size of the vehicle track frame overly large. The range for road wheel intervals is determined to be 120 to 480 mm at intervals of 30 mm since the road wheel diameter is assumed to be larger than 100 mm. Range of variables are shown in Table 3. Although the spring constant should be one of the variables, it is set at a specific value which changes according to the other variables. This is because it was clarified in the preliminary calculation that the ground contact ratio of crawlers was always maximized at the value at which approximately 3/8 of the stroke is compressed under the average ground contact pressure despite other factors. This is considered to be due to the fact that small-scale roughness exists only as concave topography on flat terrain resulting from objects on the ground. If concave and convex topography is distributed at the same density, the ground contact ratio could theoretically reach the maximum while 1/2 of the suspension stroke is pre-compressed. The program simulates the movement of the vehicle model on the roughest microtopography under all combinations of variables except for the ground contact length from which values divisible by the road wheel interval were extracted.

Table 3. Range of variables for simulation (unit: mm)

	min	max	interval
Ground contact length (*L*)	*1	*2	*3
Suspension stroke (*S*)	0	200	10
Road wheel interval (*I*)	120	480	30

*1 : Length that ground contact pressure is 25kPa
*2 : 6 times by displacement of the center of gravity by slant angle
*3 : Equal to road wheel interval

4.3 Processing method

The simulation is conducted as described in Figure 8, for example. The vehicle model travels on the microtopography profile moving from the position in which the rear end of the ground contact length coincides with the beginning of the profile, to the position in which the front end of the ground contact length coincides with the end of the profile, at intervals of 30 mm. Here, the ground contact line is defined numerically as a virtual linear line on slanted land. Pre-compressed suspension strokes are biased downward by shifting of the center of gravity. While the vehicle model drives on the microtopography profile, the ground contact line is considered to fit the linear regression line of the sectional profile.

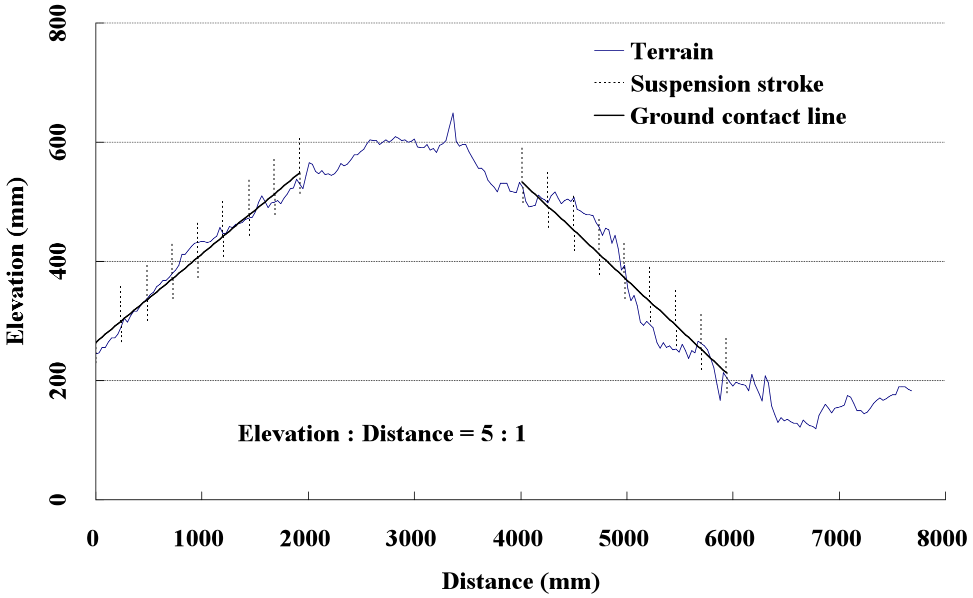


Figure 8. An example of simulated movement on measured microtopography

The number of road wheels and average load per road wheel can be derived from *W*, *L* and *I* as follows:

$$P_{AV} = \frac{W}{2(L/I+1)} \tag{2}$$

where P_{AV} is the average load per road wheel and I is the interval between road wheels. Load on the front end and the rear end of the crawler is

$$P_F = \left(4 - \frac{6\left(L/2 - H\tan(\alpha+\theta)\right)}{L}\right)\frac{W}{2\left(L/I+1\right)} \tag{3}$$

$$P_R = \left(4 - \frac{6\left(L/2 + H\tan(\alpha+\theta)\right)}{L}\right)\frac{W}{2\left(L/I+1\right)} \tag{4}$$

where θ is the sectional slant angle of the profile (Sugiyama, 1972). The load on each road wheel is

$$P_j = \left(P_R - P_F\right)\frac{Ij}{L} + P_F = \left(\frac{3H\tan\left(\alpha+\theta\right)Ij}{L^2} + 4 - \frac{6\left\{L/2 - H\tan\left(\alpha+\theta\right)\right\}}{L}\right)\frac{W}{2\left(L/I+1\right)} \tag{5}$$

where j is the order of road wheels from the front (on front end $j = 0$, on rear end $j = L/I$) and Pj is the load on the jth road wheel. Sectional slant angle of the profile equals the inclination of the sectional linear regression line as explained above. As the number of sectional measured point under crawlers is $L/30+1$, the formula for the sectional linear regression line is

$$y = \bar{y} + \frac{1/(L/30+1)\sum x_i y_i - \overline{xy}}{1/(L/30+1)\sum x_i^2 - \bar{x}^2}(x - \bar{x}) \tag{6}$$

where i is the order of microtopography data in the sectional profile ($i = 0$ on the front end of the crawler), x_i, y_i are x, y coordinates of the sectional microtopography data under the crawler and $\bar{x}, \bar{y}$ are the average values of sectional microtopography data, respectively. Therefore, the sectional slant angle is

$$\theta = \tan^{-1}\frac{1/(L/30+1)\sum x_i y_i - \overline{xy}}{1/(L/30+1)\sum x_i^2 - \bar{x}^2} \tag{7}$$

Consequently, Pj can be calculated by assigning Formula (7) to Formula (5). The pre-compressed suspension stroke by the weight on each road wheel can be derived by dividing Pj by K (spring constant). Thus, Pj/K of the stroke remains on the tension side and $S\text{-}Pj/K$ of the stroke remains on the compression side of the suspension. The absolute height of each road wheel on the ground contact line defined above can be calculated using Formula (6) by assigning x_i to x. Therefore,

$$\frac{P_j}{K} - S \le \bar{y} + \frac{1/(L/30+1)\sum x_i y_i - \overline{xy}}{1/(L/30+1)\sum x_i^2 - \bar{x}^2}\left(x_{\frac{Lj}{I}} - \bar{x}\right) - y_{\frac{Lj}{I}} \le \frac{P_j}{K} \tag{8}$$

is the necessary condition for the road wheel to trace the terrain.

Then, if the ground height of the microtopography data is within the suspension stroke of a road wheel, that is to say if Formula (8) is true, it is marked as “0”; otherwise as “1”. Ground contact ratio is defined as the value of the number of road wheels marked “0” divided by the total number of road wheels.

$$R = N(0)/(L/I+1) \tag{9}$$

where R is the ground contact ratio and $N(0)$ is the number of road wheels marked as “0”. Temporary thrust force is derived using Formula (1), multiplying L by R. This examination is done from the beginning to the final position on the microtopography profile. After the simulation, the smallest thrust force is compared with the required thrust force. If the former is equal to or larger than the latter, it is considered that the vehicle model is able to pass over the terrain in the microtopography data.

$$2\min(F) \geq \sin\alpha W \qquad (10)$$

If Formula (10) is true for the roughest terrain, the vehicle model is considered to have sufficiently able specifications to drive on the forest terrain. This process uses every combination of ground contact length, suspension stroke and road wheel interval within the defined ranges explained above.

Of course, the longer the ground contact length and the suspension stroke, the greater thrust force. On the other hand, the shorter these variables are, the smaller the weight, the greater the strength and steering ability, and the lower the production cost. It is necessary to search for a compromise between traction and other factors. Therefore, we decided that the optimized specifications would be the minimum value of the product of the ground contact length and suspension stroke that allows the vehicle model to pass over the roughest terrain in the microtopography data. As it is difficult to estimate how the road wheel interval affects the traction, it is not estimated in the final results. However, one report explains that the number of road wheels has a significant effect on the ground contact pressure distribution (Garber and Wong, 1981). In the future, the road wheel interval should be estimated in relation to thrust force in order to obtain the most optimized specifications.

5. Result of simulation

In the results of microtopography measurement, Nanakai harvested area 2 (NHA2 : which has the largest total profile length at 30mm scale length) and Tengakura natural forest 1 (TNF1 : which has the largest maximum slant angle at 30mm scale length) were identified as having the roughest terrain, and Nanakai logging road 1 (NLR1 : which has the smallest total length and maximum slant angle at 30mm scale length) the smoothest terrain. We derived the optimized forest vehicle specifications using the microtopography data from these 3 sites, assigning the assumed value of constants shown in Table 3. Table 4 indicates the results. At this time, however, there is no method to prove the validity of these results.

Table 4. Optimized specifications of the vehicle model (unit: mm)

	Roughest		Smoothest
	NHA2	TNF1	NLR1
Ground contact length (*L*)	1800	2160	1980
Suspension stroke (*S*)	50	40	20
Road wheel interval (*I*)	120	120	330

6. Conclusion

Microtopography has a notable effect on the mobility of forest vehicles. We measured the forest microtopography at varied sites in 5 different categories using a device that we had developed. The roughness of the ground could be investigated using both the total profile length and the maximum slant angle of the microtopography. Site categories could be sorted in the order of roughness from rough to smooth in small-scale roughness: harvested area > afforestation area ≧ natural forest = plantation forest > logging road. This result is attributed to the fact that small-scale roughness depends on the objects strewn on the ground.

We intended to utilize the results for designing the undercarriage of forest vehicles. We developed a computer program to optimize the specifications of a crawler forest vehicle. A vehicle model was configured with constants and variables. The thrust force of the vehicle model on the roughest microtopography was calculated by inspecting the number of road wheels that trace the terrain. The program estimates whether or not the vehicle model can pass over the terrain given through the microtopography data by comparing the calculated thrust force with the required thrust force. Optimized specifications were determined using the minimum values of ground contact length and suspension stroke that enabled the vehicle model to pass over the roughest terrain, compromising mobility with weight, size, strength and cost. Optimized specifications were successfully derived through this program. However its validity is difficult to prove due to the lack of a verification method. It will be necessary to improve the program and to include proof of validity.

References

Bekker, M. G. (1960) Off-the-road locomotion. 220pp, The University of Michigan Press, Ann Arbor

Bekker, M. G. (1969) Introduction to terrain-vehicle systems. 865pp, The University of Michigan Press, Ann Arbor

Fukuda, A. Suzuki, T. and Ichihara, K. (1984) Automatic inclination control system of hillside tractors III – A measuring apparatus for forest terrain profiles. Transaction of 95th Meeting of Japan Forestry Society: 617–618 (in Japanese)

Garber, M. and Wong, J. Y. (1981) Prediction of ground pressure distribution under tracked vehicles – II. Effects of design parameters of track-suspension system on ground pressure distribution. Journal of Terra Mechanics, 18(2): 71–79

Imatomi, Y. (1984) A study on forest terrain profile. Transaction of 95th Meeting of Japan Forestry Society: 611–612 (in Japanese)

International Organization for Standardization (1995) ISO 8608 Mechanical vibration – Road surface profiles – Reporting of measured data, 30pp, ISO, Geneva

Lombaert, G. Degrande, G. and Clouteau, D. (1999) Deterministic and stochastic modeling of free field traffic induced vibrations. Proceedings of International Symposium on the Environmental Impact of Road Pavement Unevenness: 163–176

Ohmiya, K. and Matsui, K. (1982a) Studies on agricultural terrain profiles (I) – A measuring apparatus for agricultural terrain profiles, Journal of Japanese Society of Agricultural Machinery, 44(1): 17–22 (in Japanese with English summary)

Ohmiya,K. and Matsui, K. (1982b) Studies on agricultural terrain profiles (II) – Measurement and evaluation of agricultural terrain profiles, Journal of Japanese Society of Agricultural Machinery, 44(2): 293–297 (in Japanese with English summary)

Ohmiya, K. and Matsui, K. (1986) Studies on agricultural terrain profiles (III) – Roughness of agricultural terrain, Journal of Japanese agricultural machinery, 47(4): 469–474 (in Japanese with English summary)

Sugiyama, N. (1972) Problems of construction machinery and soil. 208pp, Kashima Publishing, Tokyo (in Japanese)