Algorithms for Skidding Distance Modelling on a Raster Digital Terrain Model

Ján Tuček
Erich Pacola
Technical University
Zvolen, Slovakia

ABSTRACT

Algorithms for determining skyline skidding and tractor skidding distances on raster digital terrain models are introduced and presented. Modules named DOWN, UP, STRDOWN, STRUP were programmed in Turbo Basic language to work with a raster Digital Terrain Model. The DTM, interpolated from a set of digitized contours, and all other data were handled in the IDRISI GIS environment.

Implications of these algorithms are discussed, especially their advantages and disadvantages relative to the opening of forests, and more broadly forest operational planning. Flowcharts illustrating the method for calculating tractor and skyline skidding distance are included.

Keywords: *raster digital terrain model, distance modelling, skidding distance.*

INTRODUCTION

Location siting of forest roads is a complex problem. Its solution has a great influence on the range of potential technologies available for tree removal and on the efficiency of the process. Forest road building, using different technologies also has a great impact on the natural environment. So many factors and alternatives are considered and evaluated in this process that it has traditionally been aided by computerized methods. However, there are no common criteria nor common methodologies. Every "optimization" is also a problem of the definition of criteria and the priorities established for special and unique conditions. Historical development in opening up the forest, and traditions in the logging methods applied in different countries also play an important role.

Many papers describe models that produce a road network plan for forest areas that are being accessed for the first time. Most of them are based on an economic evaluation of alternative routes. Cost and benefit analyses are the most common economic means of evaluation [4, 15, 7, 1]. Another model is based on the identification of broad feasible corridors that are selected for detailed evaluation of their route potential. Route alternatives are identified within each corridor followed by further analysis involving the synthesis of specific information extracted by aerial photo interpretation, field surveys and integrated DTM data [12, 13]. Another approach is to find the route which might best minimize damage to the forest environment (e.g. minimum total score by estimating variable factors related to conservation of forest land) [6]. Reutebuch [10], Liu and Session [5], Yoshimura [19] developed models to assist planners in finding and evaluating route locations based on digital terrain data. Their models took into account gradients between relevant grid points and other topographical features which makes them applicable in mountainous environments. We have presented a more in depth literature revue in this field [18].

It is typical of harvesting areas in Slovakia to find fairly extensive road coverage (in some areas over 100 m.ha^{-1}). However, the construction type and the spacing of existing forest roads are very unfavorable. For example the ratio between main forest roads (paved road) and other roads is 1:3- 1:5. There also is the problem that tractor skidding technologies predominate. The method of tractor skidding recently has spread to areas of mountainous terrain conditions (45% of the territory of Slovakia). Areas with these conditions are very suitable for skyline skidding where, from an ecological perspective, it is essential to restrict dense ground skidding roads.

From the description above it is apparent that the primary issue concerning the siting of forest roads in Slovakia is not to develop a road network for previously unaccessed areas. On the contrary, transport planning in these conditions is focused on (1) the placement of new hauling roads into the existing forest road network where areas are not fully open, (2) the reconstruction of selected skidding roads and some secondary hauling roads to main hauling roads and (3) the sanitation of skidding roads which control be rebuilt, and using skyline technologies instead.

The authors are, respectively, Assistant Professor and Graduate Student, Department of Exploitation and Mechanization, Faculty of Forestry.

Transportation planning in this cases focusses on judging the efficiency of the existing forest network. Skidding distance is one of the basic criteria for this judgement. The latest developments in software environments, particularly in improved data structure and algorithm efficiency, make it possible to carry out an evaluation of skidding distances for existing road locations. Skidding distance, as it is derived from terrain conditions, makes the identification of those areas possible which do not gravitate to the existing hauling roads and which are beyond the range of economic tractor skidding distance or maximum skyline skidding distance.

Energies for siting the location of new roads can be directed toward areas that are not yet opened or exceed commonly used skidding distances. Together, in these different areas, ground skidding roads can be evaluated for optimal road spacing, and redundant roads can be identified.

Distance mapping that includes the calculation of Euclidean distances, isotropic distances, and directional path distances [2] does not permit the direct modelling of skidding distance. By combining these distance mapping algorithms, the standard tools of map algebra and a raster digital terrain model we can change plane cell length to slope cell length and propagate slope length to its neighbours. In the case of mountainous terrain conditions, the modelled results approximate reality. However, even these methods should not be used under mountainous conditions when taking into consideration different skidding technologies. In the GIS environment it is not easy to evaluate directly the terrain configuration - the directions of skidding (uphill, downhill skidding), the location of important terrain lines where the direction of skidding changes (ridge, valley), and the deviation of a line of sight from the gradient curve. On the other hand there are many useful tools included here to evaluate intervisibility between points in space and slope curvature.

We designed modules (several alternatives) to make possible the calculation of skyline and tractor skidding distances in specific terrain conditions. Algorithms that will be discussed are not in conflict with the theories of SUDDARTH and HERRICK [9], and GREULICH [3]. The models contribute toward the accurate quantification of topography factors. Fully automated computation can greatly enhance our ability to generate and evaluate skidding distances for variable real conditions.

The first objective of this paper is to propose the use of a digital terrain model and models of skidding distance to automatically identify areas that are critical for intended skidding technologies and the existing forest road network or proposed roads. This includes the areas (1) which do not gravitate to the existing hauling roads, (2) which are beyond the border of commonly used tractor skidding distance, (3) are beyond the border of the maximum skyline skidding distance from either existing roads or terrain line (valley, ridge), and (4) areas of gravitational drainage. The derived information can meaningfully supplement decision making where a new road is to be sited and where existing ground skidding roads can be proposed for sanitation. The second objective is to show the possibility of using these models for comparing the efficiency of two or more alternatives when considering the opening of forest areas or sanitizing of roads. This comparison follows from the alteration of important technological criteria for skidding distances.

METHODOLOGY

The modules DOWN, UP, STRDOWN, STRUP were created to be linked with the IDRISI geographic information system and with skidding distance models. The IDRISI environment offers very good tools for preparing and entering spatial information needed for deriving distances from a digital terrain model. Outputs from the modules are processed again using IDRISI's tools for subsequent analysis and display.

DTM data were interpolated from a set of digitized contours and stored in ASCII image file format. This file structure is read as Turbo Basic sequential files for the direct processing of writing and reading. All data matrices are held in memory as two dimensional arrays to avoid using much disc input/output time. The disadvantages of this approach are discussed below.

All other data used as input information for the modules, were prepared in the same manner. The data files mainly consisted of topographical parameters like valleys, ridges, and aspect, and other locational information such as roads. Standard IDRISI modules were used for additional analysis and the display of results.

We worked with a DTK PC 486/50 MHz, 8MB RAM, 1 MB VRAM. Peripheries were a digitizer CALCOMP 9000, a plotter HP 7495 and a printer HP 510 Ink Jet.

TRACTOR SKIDDING DISTANCE MODELLING

The output from the DOWN module - skidding distance model, is a map of distances measured from each cell of the raster image in the direction of maximum downhill slope to the nearest road. The target feature can be a valley, a road, or a defined point on the line representing the valley, as well. This approach is a response to the problem of downhill skidding in rough terrain conditions. Real routes of skidder movement may be a little different in details from the simulated routes, but generally they will be close. The main problems are calculating maximum downhill slope from a DTM and cumulative slope length for each cell. Calculation of cumulative slope length is done by summing noncumulative slope lengths along the flow direction (direction of maximum downhill slope). But in the final analysis, cumulative slope length grows from the road to a gravity line in the opposite (uphill) direction. Accumulation begins at each processed cell and ends when the flow exits the grid or crashes to the line feature representing road or a topography line.

The flowchart illustrating the method for calculating skidding distance is shown in Figure 1a, Figure 1b and the result of these calculations is illustrated in Figure 2. The overall methodology, input, output coverages and values are apparent from the described flowchart.

This module was created to alternatively model uphill cumulative slope length (module UP). The purpose of this modification was to calculate skidding distance from a ridge line. In a forest situation without roads, distance calculated as such can be a helpful parameter for siting a new road not exceeding commonly used tractor skidding distances for most far cells of a ridge.

We can use the output from DOWN and UP to delineate the stands which are not opened up for a defined maximum distance and direction of skidding to an existing road position.

The IDRISI module EXTRACT allows the planner to extract the maximum or average skidding distance for each defined forest compartment. This potential, the automated inventory of average skidding distance, is very useful in forest operational planning. The calculation of weighted average skidding distance [11] determined as the ratio of the sum of "haulage moments" (product of hauled wood of one compartment and its average skidding distance), can be automated as well. The distances derived by this method consider the variability of topographic factors like slopes, valleys and ridges. The location of forest road routes or calculation of optimal road density can thus be done more rationally so that the investment effect or the benefit-cost ratio is maximized by considering terrain features [4].

Modules are designed to calculate ground distances from each cell of a compartment to the nearest hauling road. Every hauling road cell is supposed to be a potential landing. The distance travelled by the skidder from the landing over the skidding roads to reach the compartment boundary is referred to as the fixed tractor skidding distance. The course of actual skidding roads and the flow direction routes derived by our algorithm are often identical. However, the algorithm could be adapted to calculate ground distance to a real landing on a hauling road. Fixed skidding distance (over skidding roads) can be calculated by the module COST (COSTGROW) in IDRISI and then summed over ground distances (module DOWN).

SKYLINE SKIDDING DISTANCE MODELLING

Output from the module STRDOWN - the skidding distance model is the distance from every cell measured as a length of the line of sight over terrain to the nearest road cell (distance between center of the processed cell and the center of the nearest road cell). Intervisibility between the processed cell and the deviation of the line of sight from the gradient curve (aspect of cells are checked under the line of sight) are checked in the process of computations. If some of these conditions are not satisfied, the signal value will be written to the cell. This value shows that the cell is not reached in skyline logging operations.

This approach again continues with the reality that skyline skidding paths are laid out in the direction of a gradient curve or in the permissible angle range from gradient curve (parallel, not fan out routes). This is common mainly under European conditions. The skyline tower and tail spar can be defined as input values which modify technological conditions. The height of a skyline tower and the height of a tail spar are summed with values of terrain elevation at the location of an ending point cell (processed road cell) and a beginning point cell (processed terrain cell). Of course, there are important t

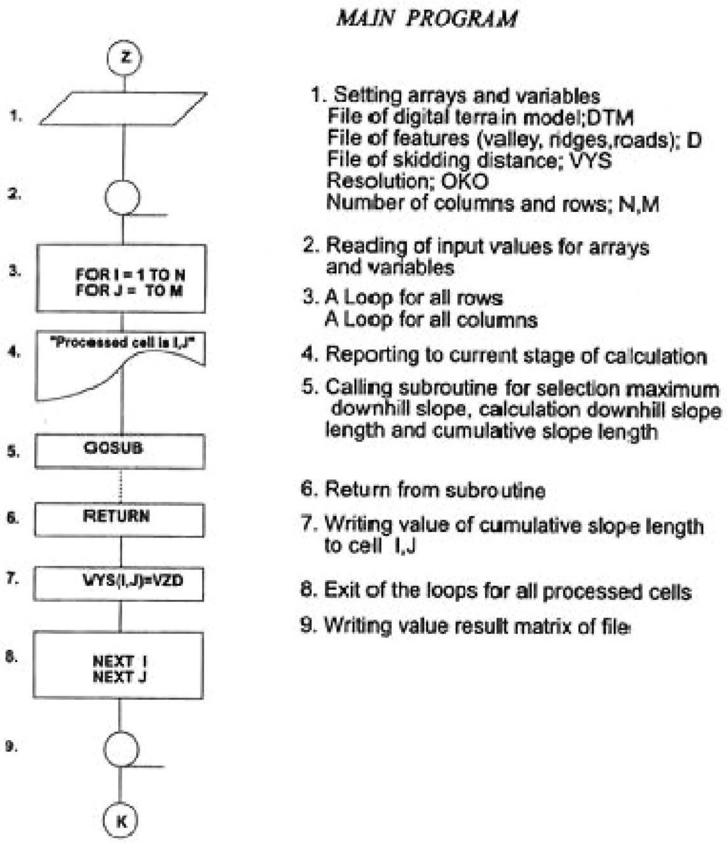


Figure 1a. FLOWCHART - Modelling of tractor skidding distance.

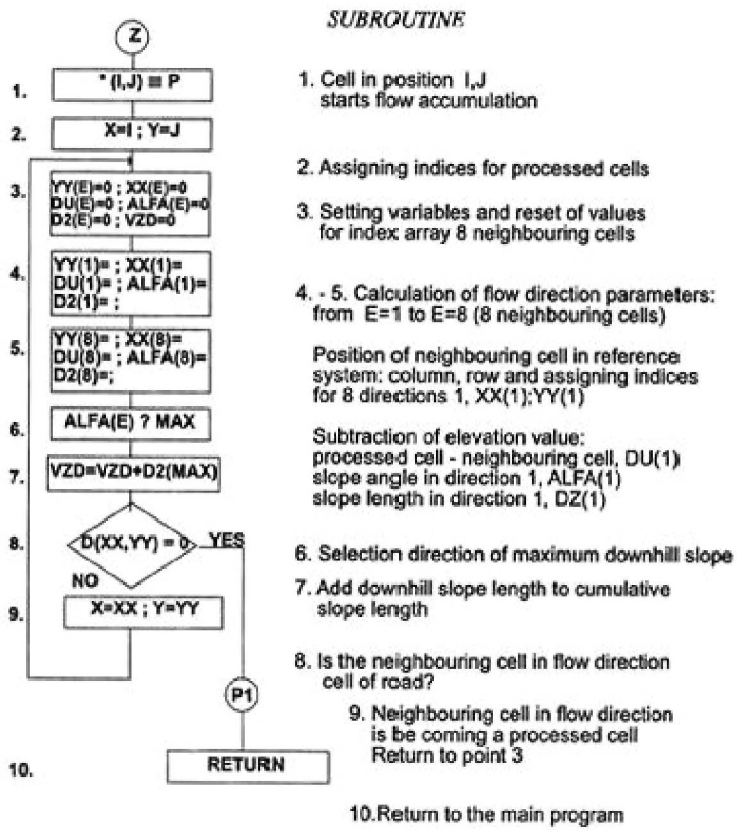


Figure 1b. FLOWCHART - Modelling of tractor skidding distance.

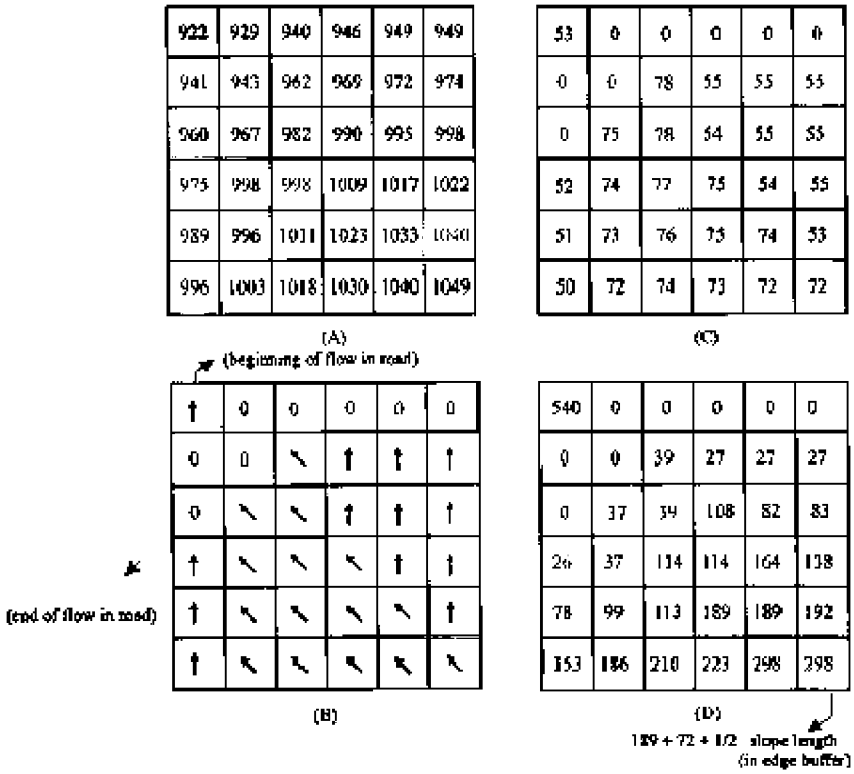


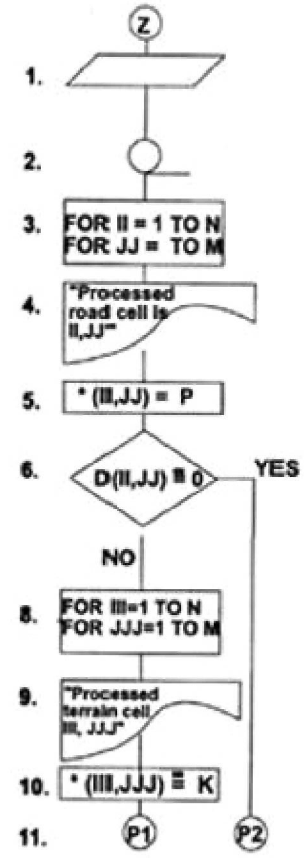
Figure 2. (A) Grid representing DTM (resolution 50 m); (B) Flow direction = direction in maximum downhill slope; (C) Slope length calculated from maximum downhill angle; (D) Cumulative slope length.

simplifications made in this approach in comparison with real conditions. Use of a tree jack is not proposed. But for a basic orientation, automated solutions are useful.

Figure 3a and Figure 3b illustrate the algorithm for calculating skyline skidding distance. Figure 4 and Figure 5 represent the basic elements of the skyline distance model. The process for calculating the input, output coverages, and values are apparent from the flowchart.

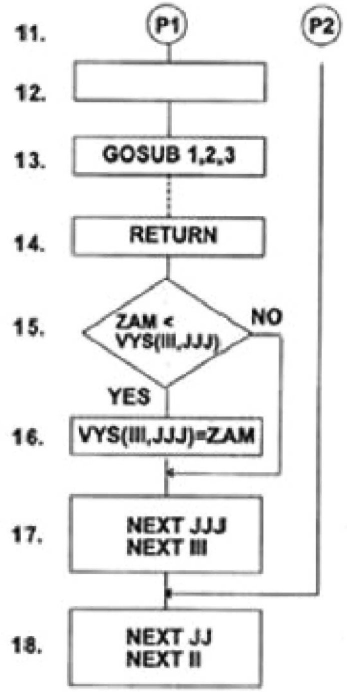
The module STRDOWN calculates distance only for downhill (gravitational) skidding. Considering that uphill (antigravitational) skidding is typical for contour roads located on slopes, we have created the module STRUP.

Both modules could be useful for the proposal of a solution for regular road route location of contour roads in the forest. A project of locating new sections of contour roads might be based on the idea that the distance between the new road and the ridge and/or valley line should not exceed the technological length of a cableway system route. Skidding distances measured from the valley line are simulated in one output file while distances from the ridge or existing hauling road in another one. An overlay of these files using the operation "minimum" (OVERLAY module) results in an output file in which the maximum value of distances determine the limit for extraction by skidding downslope and upslope. A new hauling road should be located inside the area demarcated by the limit for extraction. The area boundaries ensure that the limiting maxi-



MAIN PROGRAM

1. Setting arrays and variables:
   File of digital terrain model; DTM
   File of roads; D
   File of aspect; ASP
   File of skyline distances; VYS
   Resolution; OKO
   Number of columns and rows; N,M
   The size of allowable deviation from the gradient curve; OE
   The tower height; H1
   The tail spar height; H2
2. Reading input values of arrays and variables
3. A loop for all rows
   A loop for all columns
4. Reporting to current stage of calculation
5. The cell in position II, JJ is the beginning for line of sight
6. Is the cell in position II, JJ road cell?
7. Reporting to current stage of calculation
8. Nested loop for all rows
   Nested loop for all columns
10. Cell in position III, JJJ is the end for line of sight
12. Replace calculated distance by penalty value
13. Exit of loop for interpolation steps
14. Return to the main program



12. Type of line of sight
    1. rows/columns
    2. diagonal
    3. with interpolation
13. Calling subroutine according to type of line of sight
14. Return from subroutine with calculated distance
15. Checking calculated value to existing written value in matrix of results. If calculated value is smaller, then change them with each other
16. Write calculated value to matrix of result in position III, JJJ
17. Exit loops for the end of the line of sight
18. Exit loops for the beginning of the line of sight

Figure 3a. FLOWCHART - Modelling of skyline skidding distance.

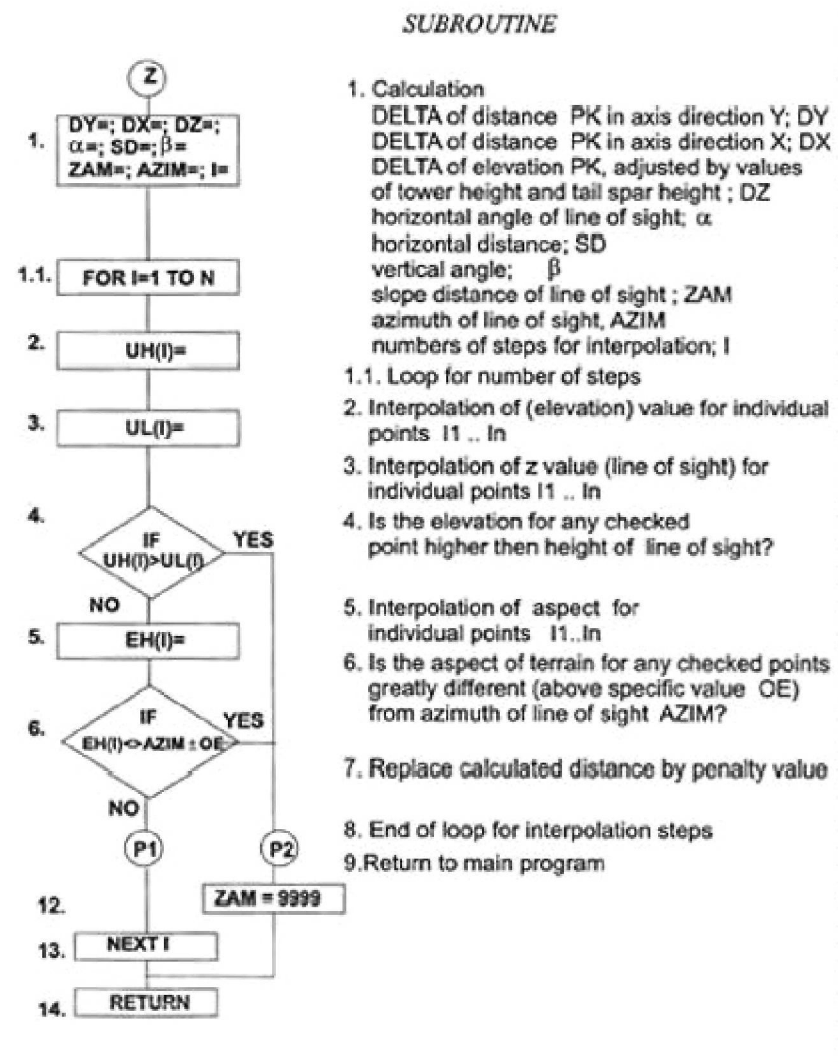


Figure 3b. FLOWCHART - Modelling of skyline skidding distance.

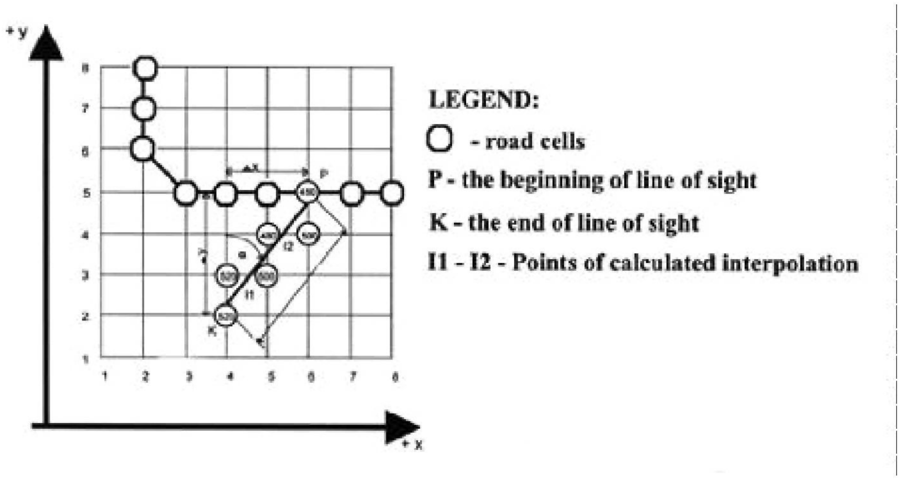


Figure 4. Modelling of skyline skidding distance, situation.

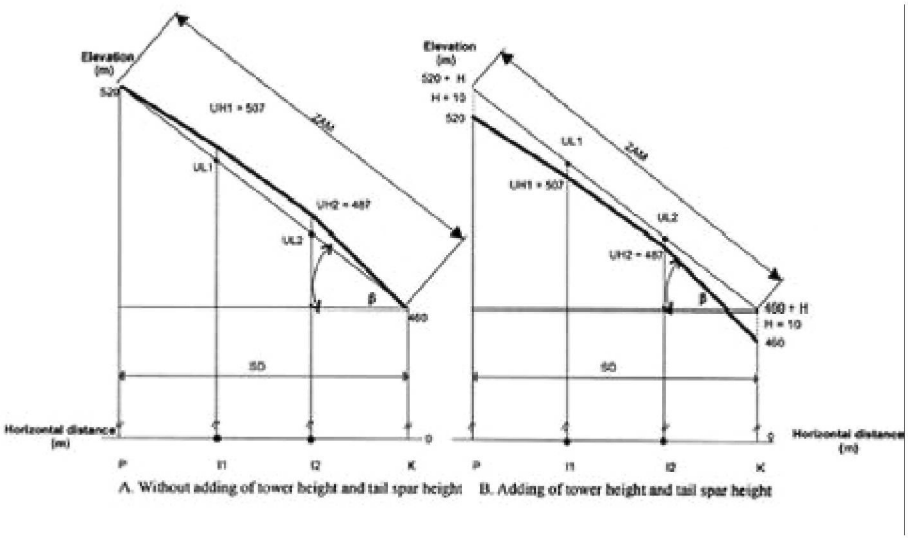


Figure 5. Modelling of skyline skidding distance, cut profile.

mum effective span of a cableway system will not be exceeded by the new road location.

Another possible use of the modules arises from the necessary evaluation stage when opening up the forest. Simulated distances calculated for the maximum span of planned skyline system and for an existing or proposed road can be evaluated as the value of area accessibility (percentage of forest land within the range of maximum effective span). Mutual comparison of the two or more values of area accessibility (one for each proposal) could be a measure for accepting or rejecting proposals.

Computing available area or average skidding distance for the gradual design of hauling or skidding roads by these modules can be useful for determining: (1) the dependence of real ground skidding distance on the change in the real density of skidding roads, and (2) the mutual dependence of the length of hauling roads and the opened up area. By assessing relationships between mentioned quantities for measured road construction and for a given real condition we can better determine the optimal forest road density in mountainous areas [11].

AREA ACCUMULATION

The output from the module AKUM is a map of "area accumulation" which may be a source of supplemental information for decision making in the siting of a new road. Cells that accumulate the largest area are potentially the most suitable for road location. When the area is being accessed for the first time, the new hauling road should be located on the valley lines or near to them. It is also possible to create "the map of gravitation drainage of terrain" [12]. Those cells which do not accumulate area, or where their accumulation is clearly poor are probably locations of gravity boundaries. These lines are technologically important for the creating of working units as well.

When we know the volume of timber to be logged (a forest management plan) we can create the coverage of the uneven spatial distribution of timber supply (simulation techniques) or even the distribution. Using this module we build a layer indicating the amount of timber that would ultimately be transported over each location. Each location will be accessed by way of its minimum downhill path [16]. These paths may indicate the future network of skidding roads. On the other hand, hauling road cells that acummulate the most timber supply can be potential skidder landings.

We do not provide a flowchart for this algorithm. It is the same one as for determining tractor skidding distance (Figure 1a and Figure 1b). The difference is only in the subroutine, where steps 4 and 5 calculate downhill slope angle only. Step 7 of the main routine does not accumulate slope length, but only a fictitious value (usually 1) or a cell area.

MODEL LIMITATIONS

The first problem occurs with using the Turbo Basic environment and writing code with a limited array size (64 Kb). It means that only 16 000 cells for one array could be accommodated using this algorithm in environment of Turbo Basic with single real data type (4 byte). To derive the total diversity from contour image, and therefore the maximum amount of useful information available in a raster DTM, it would be convenient to choose a spatial resolution no lower than 30 m but no higher than 15 m [14]. For a resolution of 30 m this would permit about 1428 hectares to be analyzed and for 15 m only 357 hectares. The problem potentially is solved by partitioning the analyzed territory into smaller parts or by choosing a higher resolution (50 - 100 m) at the expense of a loss in detailed information.

The second problem is the length of computer processing time. AKUM, DOWN, UP, STRDOWN, STRUP algorithms and their modifications hold all data matrices in memory. This approach is effective from the point of view of computer input/output time, for such time is low, but it leads to the problems described above. Another problem arose from using a sequential file to link the program with IDRISI. The interchange format between environments IDRISI and modules was an ASCII file which is manipulated consecutively like a sequential Turbo Basic file. Storage and handling of binary files would markedly reduce computing time.

Algorithm DOWN iteratively propagates the slope length distance individually for each cell. When the flow path crashes to the cell for which cumulative slope length already has been calculated, it is possible to exit the propagation process. Before calculated length is added to a partially calculated cumulative slope length for an analysed cell and entered to the result matrix as a skidding distance for processed cell. This approach can speed up the algorithm too.

Algorithm STRDOWN calculates distance for every combination of road cells and terrain cells and checks calculated distances according to the conditions listed in flowchart. This approach markedly retards the handling of information. It is possible to write tighter and quicker code. We think that the analysis of cumulative slope length and the derivation of the higher slope length for a considered area (catchment area) can be a useful follow-up for the STRDOWN calculation. Distance calculations for cell combinations only within maximal slope lengths may improve and accelerate the algorithm.

EXAMPLES OF SKIDDING DISTANCE EVALUATION

The above described modules were examined in three model areas. Specific problems were solved using these models. The technological evaluation of the existing road network we verified in the territory of water conservation research object Vrchdobroè (local name), Forest Enterprise Krivan [17]. The entire area was suitable for using tractor logging technologies. The technological consequences of hauling roads route location were evaluated. The forest stands which were not fully opened up (for skidder) and stands where maximum skidding distance exceeded commonly used skidding distance were identified. We paid attention to these stands then in the decisions about new roads to supplement the existing road network. The new quantification of average and maximum skidding distance for the proposed road network was introduced as in Table 1 and Figure 6. All stands were opened by the new alternative, and both distances did not exceed 500 m. A completely new scenario would be to build only valley roads in the studied area. This is not a real alternative, though, because of the existing roads, but we introduced it as an example. Evaluation of distances to the nearest road downhill for this simulation is also found in Table 1.

In the case of Kyslinky valley in the Polana Mountains (Central Slovakia), the main objective was to verify the skidding conditions after removal and sanitation of the skidding ground roads in the natural protected area and partially substitute ground skidding technology with skyline skidding [18]. Steep slopes above 45% occupy about 40% of the total area of this forest. Despite the necessity to use more environmentally feasible skyline skidding, 90% of logged timber is extracted by skidder. The goal of this work was not to decide about the location of new roads but only to make an appraisal of skidding distances after removing some of the

Table 1. Skidding distances for existing and proposed roads: P = partially accessed stand
F = no current access

Stand numbers	Existing roads	Existing + new roads	Valley roads
	maximum distances / average distances		
1	P	488 / 191	1105 / 342
2	350 / 120	350 / 120	731 / 341
3	P	457 / 119	586 / 190
4	F	199 / 52	432 / 74
5	P	285 / 98	424 / 172
6	P	409 / 104	546 / 190
7	499 / 192	435 / 149	612 / 206
8	904 / 434	574 / 184	693 / 249
9	1046 / 702	439 / 186	826 / 382
10	575 / 405	546 / 191	366 / 177
11	P	385 / 366	888 / 483
12	P	295 / 136	803 / 474
13	F	184 / 67	704 / 485
14	386 / 156	261 / 98	342 / 125
15	313 / 81	273 / 69	370 / 226
16	400 / 119	400 / 119	280 / 116
17	P	311 / 82	1012 / 323
18	P	312 / 117	1033 / 462
19	F	141 / 58	625 / 212
20	F	425 / 128	464 / 121

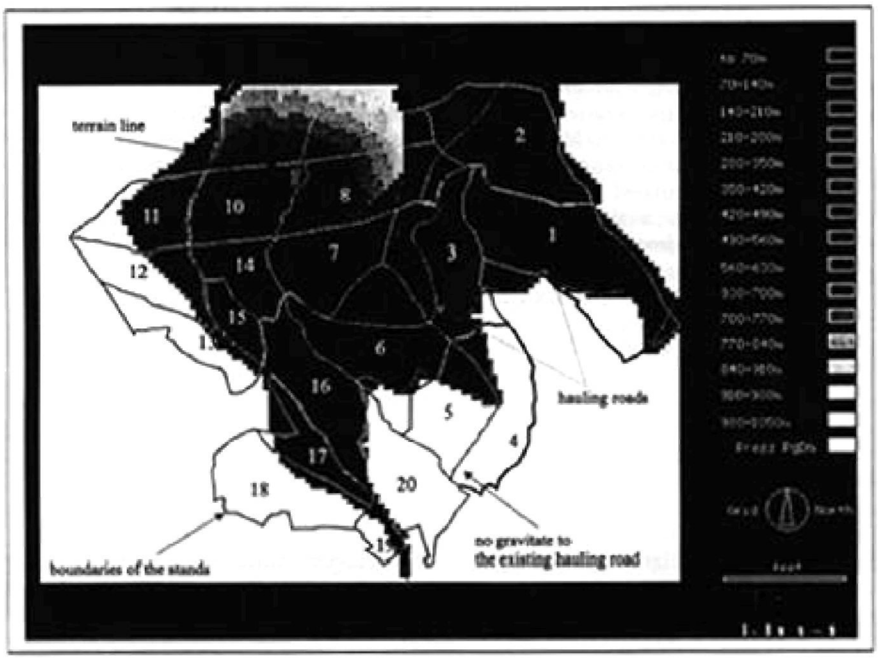


Figure 6. Evaluation of the distances in the direction of maximum downhill slope to the nearest road.

ground skidding roads. Real slope length by module DOWN was computed for the situation without roads. This analysis allows us to determine the state of terrain undulation and morfological terrain quality (occurence of very long slopes above 1000-1500 m). The second step consisted of separating ground skidding areas from cable skidding areas. This was done through a slope evaluation by use of regular DRISI modules. In the analysis of skidding distances we joined the existing investigation and the recommended proposal for hauling roads. Results of the distance analysis were displayed using map compositions and an ortographic perspective view draped with important information layers (roads, boundary no forest area, boundary wildlife reserve). For alternative technologies that considered only skyline skidding (commonly used skyline with yarding distance to 500 m, up-hill and down-hill yarding), it was apparent that some areas were not accessible. In the second alternative we analysed tractor skidding distances for demarcated ground skidding areas. Results of both variants were combined into one map layer by Boolean overlay. The results of the skyline distance analyses were superimposed only over areas reasonable for this skidding technology. Results of the analysis were, of course reviewed, and verified in the field. No important discrepancies were observed.

The problem of locating new hauling roads was explored in gravitational area Velky prostredniak, in part of Kralova hola in the Low Tatras Mts [8]. This was a very interesting case of opening up the forest reserves. The solution of the problem was influenced by two competing objectives. Forest stands in this territory have been included in the category of protected forest and are under specific management rules. By these rules, high road density is unacceptable. On the other hand, the high timber supply of spruce damaged by air pollution calls for adjusted silvicultural treatment which can regulate regeneration of stands and inhibit the decline of the upper forest limit. Therefore, the proposal for new roads had to be in accordance with use of environmental technologies. All existing skidding roads were proposed for sanitation (7861 m, 25 $m.ha^{-1}$), and tractor skidding technologies were excluded for this typically mountainous area (65% of area was defined as typical cable skidding area). Relative accessibility of stands (30%) for the cableway system LARIX (maximum yarding distance to 550 m) was calculated as a ratio of area within the range of the maximum effective span calculated from existing roads. A project of locating new sections of hauling roads was based on the idea (described above) that the distance between the new road and the ridge and/or valley line should not exceed the length of the maximum effective span for proposed cableway system route. Our proposal of location of new road with total length 2 433 m increased accessibility up to 75% and hauling road density from 6 $m.ha^{-1}$ to 17 $m.ha^{-1}$. This could be acceptable for environmental agencies too, since a proposed hauling road (paved road) makes it possible, to change tractor skidding technology used at present, to environmentally acceptable skyline technology. The construction of the new roads was conditioned by sanitation of all ground skidding roads too.

DISCUSSION

The skidding distance models presented here are tools to help the road planners judge the efficiency of existing or planned road networks while considering the „real" skidding distance and the proposed technology of skidding. At the same time these models can be useful tools for identification of appropriate areas to location of new roads. In determining technological criteria, slope and other topographical features of the landscape should be taken into account and made out forest hauling roads under mountainous conditions. In GIS IDRISI environment linked to these models is a possibility to create many other information layers. We can use them like supplementary sources of information for decision making. The possitive or negative places may be localized as slope stability informations, extreme slopes, rockiness, places for landings, environmental barriers. Using multiple attibute query we can define those locations that meet more than one condition (suitable area for road location). The multiple attribute query can be accomplished using Boolean Algebra.

The described models are not automating and optimizing models for forest opening up. There is lacking a program which can rapidly develope and evaluate route location based on digital terrain model. Expert system focused in selecting passing points (points where direction of the route is changed and where landings can be suitably located), on forest road [19] and based on the evaluation „real" skidding distances can be an optimizing tool in location of hauling road. In the process of selection passing points, grade and distances between points and skidding distances (from existing roads) can be controlled by fuzzy theory. Gradeline between passing points can be autoamatically layed out by path distance model [2] which propose three additional factors in the distance measure (surface, gradient and horizontal direction factor). Model enable expression of criterias influencing location of road as friction too. Friction indicates the absolute / relative cost or degree of risk assessment of moving through each cell. Minimizing the friction between two passing points is controlled by gradient factor which considers the effect of the value gradient from a cell to its neighbour.

Our future work will be concerned with the removal model limitations described above, and designing a future Spatial Decision Support System (SDSS) to laying out forest hauling roads under economic and technological criteria. We propose that ESRI'S UNIX-based ArcInfo would be helpful in this way. Powerful tools of map algebra and Arc Macro Language (AML) provide a full set of programming capabilities that allow:

- combining ArcInfo functions to create specialized models,
- developing menu-driven interface designed programs to meet the needs of end users (forest engineers in planning of forest road networks).

Initial explorations in this environment are very encouraging.

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