A New Planning System with the Aid of Computers for Designing Skidding Road Networks in Tractor Logging Operations

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Introduction

Timber harvesting systems in Japan are generally divided into cable and tractor logging, and adoption of either one depends mainly on terrain conditions. Since terrain conditions are generally very steep in Japan, the cable logging system was most popular. In the 1960's the volume ratio of timber production by the cable and the tractor system was almost 70:30, but nowadays it is about 50:50.

As the major reason for this trend, it is considered that logging by using tractors has become adopted in such places where logging was carried out by human labor and animal power, and field loggers tend to prefer tractor logging to cable (crane) logging not only because the former requires simpler logging technique, and fewer workers for main and sub-operations of logging than the latter, but also because tractor logging on steeper slopes was made possible by constructing tractor skidding roads inside forest.

At present, the majority of crawler tractors for logging are 5 to 15 tons in dead weight and wheeled tractors are 2 to 6 tons in Japan. Since crawler tractors were introduced from the United States in the 1940's, the number of them has increased steadily, but the number shows no increase since 1973. The number of wheeled type tractors developed in around 1965 in Japan also did not increase since 1975. A small wheeled tractor of about 3 tons to be used for thinning operations was invented, and it attracted great demand. This tractor is called a small long-hauler vehicle, and increased in number in private forest. The number reached about 18,000 in private forest, showing further increase (Table 1).

The tractor, in general, was primarily developed for off-road jobs. However, there is no wonder that the tractor can operate better on roads even when the road is very poor in quality, and in some cases how to minimize the amount of off-road operations is an important subject. When running cost for a vehicle like a tractor was examined on a higher standard road, a lower standard road, and off the road, the cost showed the increase in that order. On the contrary, the cost of road construction decreased in that order[6,11]. From this point of view, whether the road should be constructed for logging or not is determined by the total cost for tractor transportation and road construction, and it is necessary to consider the question how much is the length of road per unit area of the forest and how to locate roads to minimize the total cost of road construction. By giving the best condition for logging operation, the efficiency of vehicles will become extremely high.

Several simulation models[1,3,7-9] have been developed to analyze these issues. Most of them, however, dealt with only macro-planning of higher grade forest roads, which may cover the whole project area, are not specially developed to determine the optimum micro-lay-

Table 1. The total number of harvesting machines used in national forest and private forest in 1975, 1980 and 1985 (Japan)

Ownership	Machines			1975	1980	1985
National forest	Yarder			1, 389	1, 141	1, 022
	Winch			387	244	197
	Tractor	Crawler type	Small size	146	50	36
			Middle & large size	618	704	690
		Wheeled type	Small size	356	261	193
			Middle size	149	118	89
			Large size	296	375	377
Private forest	Gravity cable			18, 391	14, 028	4, 957
	Power cable			4, 824	3, 752	5, 107
	Mono cable			847	1, 259	1, 214
	Mono rail			421	1, 792	1, 911
	Yarder	Small size		13, 383	11 999	10, 677
		Large size		11, 199	11, 459	10, 259
	Small log-hauler	Less than 20 ps		2, 132	8, 820	16, 156
		More than 20 ps		798	883	1, 571
	Tractor	Crawler type		2, 456	2, 282	3, 126
		Wheeled type		1, 408	795	1, 262

out such as location of skidding roads and landings.

One of the most important subjects is to layout tractor skidding roads. Therefore, several issues of skidding road network essential to tractor logging will be discussed in the present paper, especially on the optimum design of tractor skidding road network (hereafter abbreviated to TSRN), which may present the most suitable and desirable method of skidding for tractor logging operations not only from the view point of rationalization of logging operations but also from that of environmental conservation in felling sites.

The finding and methodology can be used by researchers and operational managers in analysis and planning of harvesting.

Skidding road system in tractor logging operations

Tractor skidding roads are of the lowest grade in the whole forest road system, and they are used exclusively for tractor logging. They run very far into the forest area, away from the pre-existing roads (such as forest roads and spur roads).

Therefore, they are constructed with the cost relatively lower than that for common forest roads, and can be arranged easily anytime and anywhere. Consequently, they have been neglected so far, receiving only slight care in designing and construction.

However, the tractor logging has come to be adopted very often lately, and demand for using tractors on even steeper slopes in forest has increased. As a result, many problems have arisen: destruction of forest environment, safety of laborer, impact on productivity for sustained yields, etc. Planning of TSRN with reasonable standards of construction and arrangement has come to attract attention of many people.

As the premise and basis of the discussion on TSRN, the definition of skidding roads must be standardized.

1) Classification of tractor skidding roads

TSRNs should be arranged in harmony with terrain features with the minimum amount of earthworks, but they are more or less influenced by many factors; terrain conditions, working conditions, relative positions of existing forest road nets and other harvesting restrictions. Hence, it is very difficult to arrange them systematically. There are two different methods to generalize the characteristics of TSRN.

One is to consider whether skidding roads are systematically arranged or not in a certain harvesting area[4,10], while the other is to consider the pattern of the skidding road net itself[10,11], without paying attention to the arrangement for a given harvesting area.

The arrangement of skidding roads varies with the road net arrangement-index (f-value) which is calculated by the following formula:

$$f = DR / 2500 \ (1 + \eta) \quad \ldots\ldots\ldots\ldots (1)$$

where f: road net arrangement-index,
D: density of the road nets (m/ha),
R: average prehauling distance (m), and
η: sinuosity factor (ratio of increment in distance to the straight-line distance of the road).

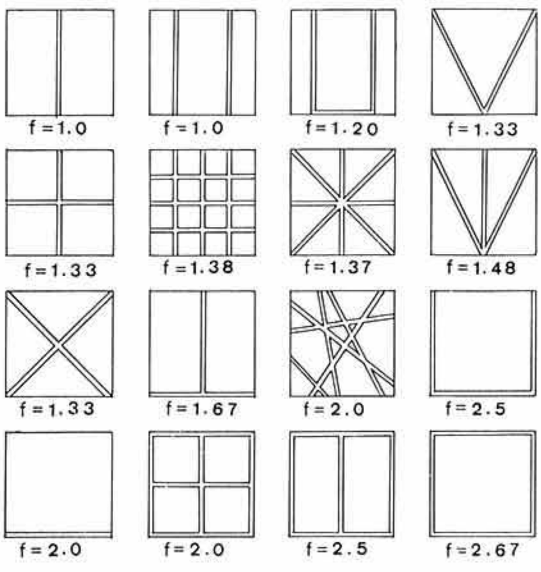


Fig. 1. Road net arrangement index (f-value) for various models of road nets

The relation between layout of simple road systems and "f-value" is shown in Fig. 1, in which bigger f-values indicate duplicated and irregular arrangement of roads, while smaller values indicate systematic arrangement. Therefore, TSRN arrangement can be classified or evaluated by obtaining the f-value. The results of the classification of TSRN arrangement showed that the range of f-value was almost 0.78–2.67. This index gives very importing indication for a skidding plan, especially for basic and macro road planning including forest roads in larger areas in forest.

The other index (p-value) concerns with the pattern of skidding road net itself. This index is more important in planning skidding operations. It directly affects the time of the harvesting cycle (prehauling, running, skidding, unloading and delaytime), and also indirectly affects many aspects of logging operation such as a flow of logging process, the number of turns per day, the number of tractors and workers required, the number and scale of landings, etc.

Skidding roads are classified into two general types; the branch type and circular type. For the purpose of collecting logs, branch type roads which are formed starting from landing sites and pre-existent roads are more popular, while the circular type which makes loopes might be formed when skidding road density increased.

On the other hand, from the viewpoint of geometrical arrangement, skidding roads are divided into three basic patterns; the first one is the radial pattern; roads run radially starting from a landing site. The second one is the reticulated pattern or the parallel-lines pattern: roads run forming a reticulation or parallel lines starting from a pre-existent road. The third one is the randomly distributing pattern: roads run randomly in a forest area. Then, these patterns are classified by using the index "p-value" which is obtained on the basis of a theoretical geometric model. The p-value is calculated with the formula as follows:

$$p = n/N \quad (0 \leqq p \leqq 1) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where p: proportion of n to N,
N: the number of intersections found on a road net when arbitrary straight lines are drawn transversing the road net, and
n: the number of the intersections which are located very closely each other.

Now, we can confirm patterns of skidding road nets in Fig. 2. The range of p-value was 0–1 for the usual TSRN, and it also became clear that the p-value close to 0 gives the convergent pattern while the value close to 1 gives the divergent pattern. The conventional TSRN (randomly made road nets) on flat terrain showed the p-value of 2/3. Various skidding road systems listed below correspond to these three patterns described above. Namely, divergent road line pattern: radial road system, fan-shaped system, convergent road line pattern: parallel road system, reticulated road system, randomly distributing pattern: dendritic road system, herring bone system.

Varieties and diversities of skidding roads systems would be generally estimated only by that different of patterns. But in practical case, multi-complexed styles are more popular; the complexity is composed of different structure, different grade of roads, direct bunching and pulling of logs without constructing road, and different skidding routes to and from landings.

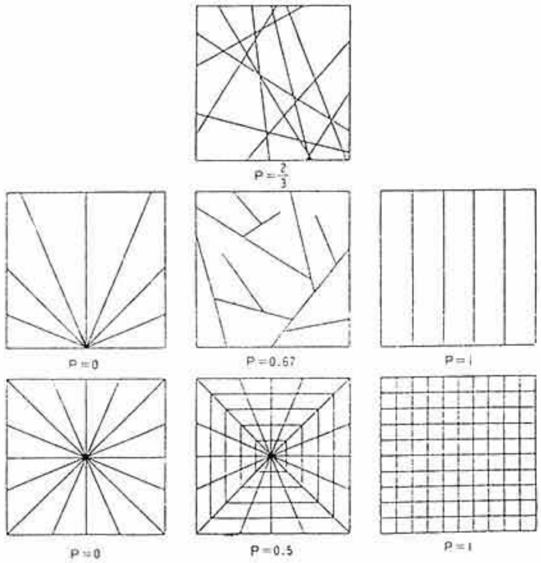


Fig. 2. Road net pattern index (p-value) for various models of road nets

Table 2. Standard and classification of skidding roads

Skidding road class		Standard of skidding road: Width (m)	Standard of skidding road: Longitudinal grade (degree)	Earthwork (yes or no)	Outline and definition
Skid trail (skid way)		2～4 m	—	No	The skid trail is a vehicle path detouring around impassable obstacles in the woods.
Skidding road	Branched	2～2.5 m	Below 25°	No	The branch road for slash disposal, debris cleaning, and/or swath way cutting of obstructive standing trees.
	Main			Yes	The most common type of road for skidding logs from the felling site. It requires some kinds of road construction works such as smoothing the road surface.
Arterial skidding road		Below 3 m	Below 18°	Yes	The quality of this road is lower than that of standard forest roads or spur roads, although some earthworks such as levelling and smoothing of the road surface, etc. are conducted to some extent.

Table 3. Type of skidding route system

Type of skidding route	Outline and definition
Free route type	Round trip to and from stumps crosses the woods, detouring around trees and obstacles. Logging is done, following the skid trails freely made. No need to prepare skidding roads with earthworks.
Semi-free route type	To access felling sites, roads are constructed, but logs are hauled down from stumps to landings along skid trails.
Fixed route type	Round trip to and from stumps for logging uses only constructed skidding roads.

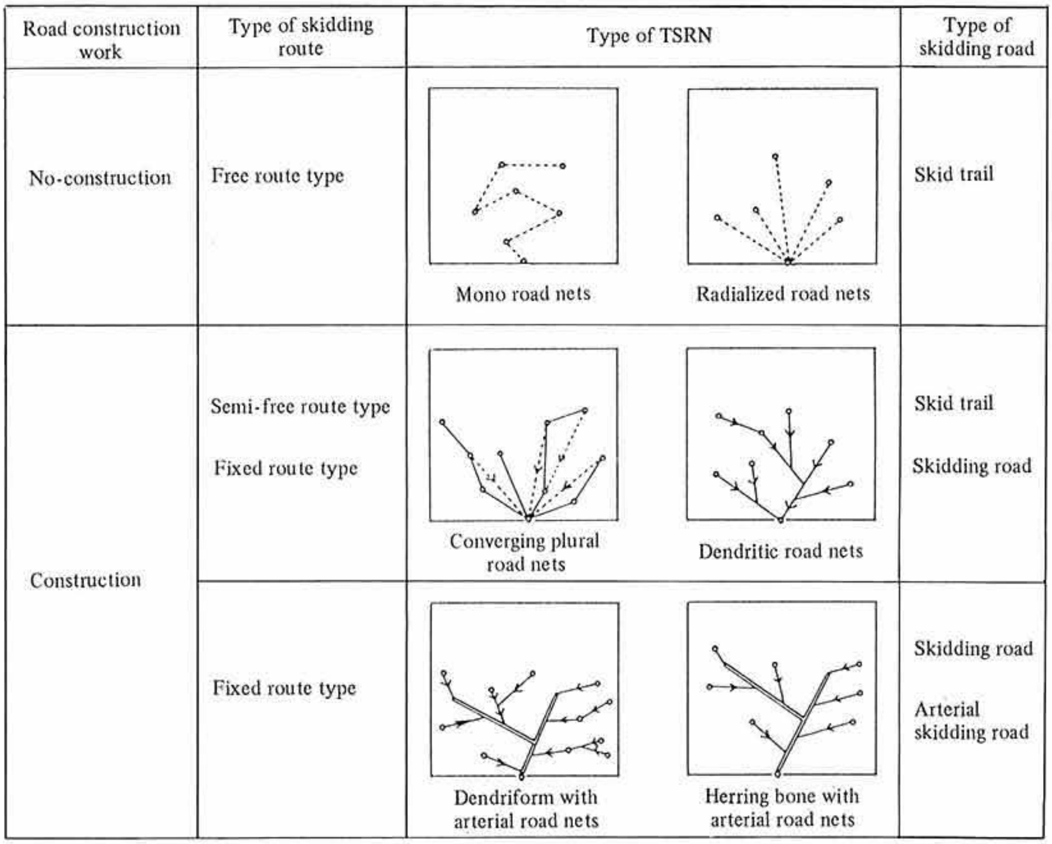
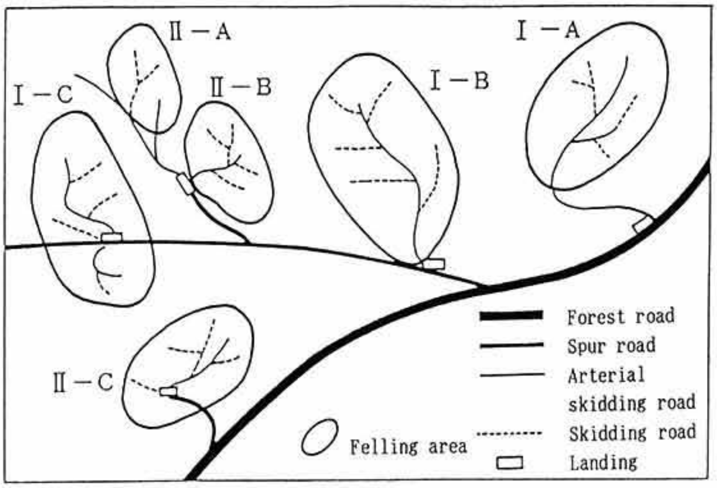


Fig. 3. Classification of tractor skidding road system by types of skidding road and of skidding route

Synthetic classification which integrates all these factors will be needed for practical skidding road systems. Based on the methods of tractor skidding which are actually employed in practice, differences in the standard of skidding roads are shown in Table 2, and different types of skidding routes for collecting and carrying out are given in Table 3. Then, by taking these differences into consideration, the skidding road systems are classified as shown in Fig. 3 schematically.

2) Relation of tractor skidding roads to landings and existing forest roads

For tractor skidding operations, the relation between skidding roads and landings (shown as lines and nodes respectively in Fig. 3 according to Graph's concept) is important. In planning TSRN, we should consider that the density, arrangement, and patterns of skidding roads have close mutual relation with location and number of landings. When landing location and arrangement of skidding roads are to be determined, the question whether there exist or not forest roads has



Ⅰ: Landing located on and near existing roads
Ⅱ: Landing located separately from existing roads
A: Out of felling area
B: Around felling area
C: In felling area

Fig. 4. Overview map showing forest road systems, landing location and felling areas in a typical tractor logging method

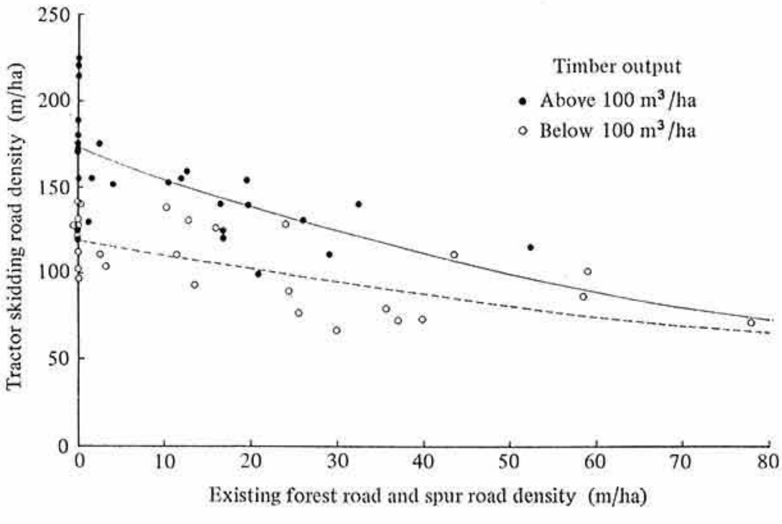


Fig. 5. Relationship between tractor skidding road density and existing forest road and spur road density for different volume of timber output on clear and selective cutting areas

to be examined, and when roads exist, the location of them will have an extremely important role.

The relation of forest roads to the location of skidding roads and landings in logging sites can be shown in Fig. 4 as typical models. Landings are generally constructed close to a forest road for trucks. Occasionally the landings are placed far away from the forest road due to easiness of constructing skidding roads and landings, and to decrease skidding distance. In this case, a lower standard road like a spur road is needed between the landing and the forest road.

In general, the location of landings should be determined by considering the following conditions: (1) the nearest place from existing roads, (2) the place to give the shortest average skidding distance, (3) the lower place in a harvesting area to prevent up-hauling for skidding, and (4) the place with the open space big enough to sustain such works as unloading, processing and reloading for further transport, and besides, the place is as flat and gently slopes as possible.

Landing sites are classified by the distance to forest roads: I & II in Fig. 4, and each case has three categories; A, B and C. Existing roads are out of the felling site (A), near of it (B) and in it (C). Our field study on national forests in Japan showed that more than 60% of the forests had the landings near and facing to existing forest roads. Thus, the density of existing roads is thought to give a great influence in selecting location of landings.

That field study on national forests indicated also that the density of existing forest roads is negatively correlated with the density of tractor skidding roads in harvesting area as shown in Fig. 5. The rate of decrease of tractor skidding road density was greater when the existing forest road density was 0 to 40 m/ha than when it was over 40 m/ha.

Evidently the density of existing forest roads affects tarctor skidding distance, and it exerts an influence upon the arrangement and patterns of TSRN and selection of landing sites. Therefore, it should be taken as one of the most influential factors in planning skidding roads.

A new method of tractor skidding road planning

The most important issue of tractor logging is how to practice logging operations in safety and economically, with minimum forest destruction. To realize it, the whole harvesting plan that can be coped with several different working conditions and/or complex and diversified forest conditions in logging sites must be worked out at first, before going into technical examination of each

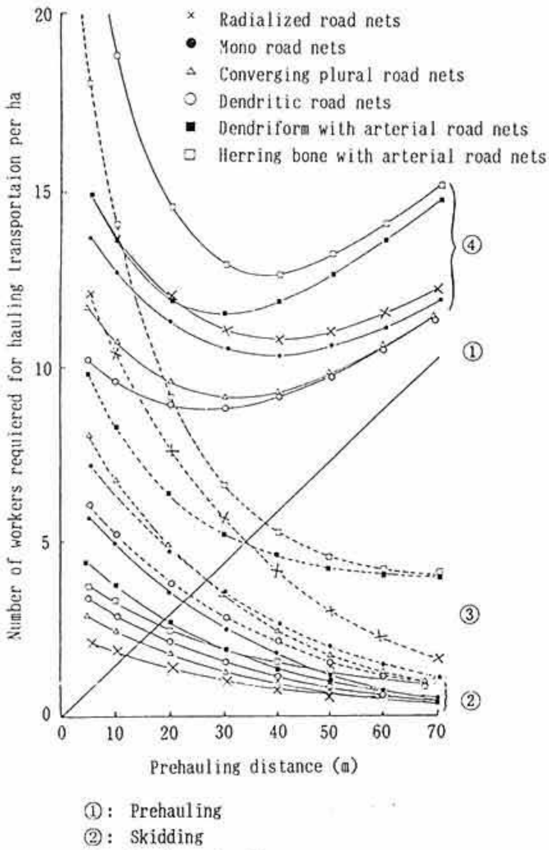


Fig. 6. Relation of prehauling distance to the total number (minimum) of workers required for prehauling, skidding and road construction

phase of logging. The most important key to getting satisfactory results is the method of planning TSRN.

Here, the most useful and practical method of planning will be discussed. In particular, the new method of planning the most suitable TSRN, which is applicable to most of tractor logging sites in Japan, with the help of electronic computation will be presented. The optimum location and design of tractor skidding road nets, which should be currently available for every tractor logging site in Japan, showed applicability of the new method developed with the help of electronic computations.

1) Selection of the most suitable TSRN and skidding method

In harvesting areas, trees are cut, logs are carried from stump sites to landings and/or forest roads. The most important question in designing the appropriate skidding method is how to divide work allotment among each operation, for example, how to allocate the ratio of prehauling distance to skidding distance when only hauling operation is concerned.

Namely, the subject is to find out what is the most suitable prehauling length by which, what is the most suitable density of skidding roads and what is the most suitable tractor skidding route to and from stumps.

In calculation, these questions can be expressed by means of an algebraic equation to minimize the combined cost of prehauling and skidding operation. But, in practice, there are lots of factors and restrictive conditions to be considered, and they are very complicated and mixed. Hence, analysis of them requires a sophisticated special tech-

Table 4. Types of skidding road, types of skidding route, and average prehauling distance adapted to different terrain conditions

Gradient of terrain (%)		~10	10~20	20~33	33~50	50~
Type of terrain		Flat	Gentle slope	Hilly slope	Steep slope	Very steep slope
Spacing between skidding roads (m)		20	30~40	40~70	70~75	75~80
Skidding road net arrangement index (f-value)		~1.0	1.0~1.33	1.33~1.57	1.57~1.67	1.67~2.0
Type of skidding road nets		Mono road nets Radialized road nets	Mono road nets Converging plural road nets Dendritic road nets	Dendritic road nets Converging plural road nets	Dendriform with arterial road nets Herring bone with arterial road nets	Herring bone with arterial road nets Dendriform with arterial road nets
Type of skidding route		Free route type	Free route type	Semi-free route type Fixed route type	Fixed route type	Fixed route type
Selection cutting	Average prehauling distance (m)	5.0	10.0	17.5	19.0	20.0
Clear cutting	Average prehauling distance (m)	5.0	7.5	15.0	17.5	19.0

nique. Only by such a technique, it becomes possible to get the best solution to the question.

Fig. 6 shows one of the examples of how to minimize the number of workers required for logging at the logging site in the national forest. There is the relation that the timber volume to be hauled from a logging site in m^3/ha varies with the degree of skidding road density in m/ha and the prehauling distance by tractor-winch in m, and also the skidding road density is always reversely proportional to the average prehauling distance. Therefore, when we first assign a definite value to the prehauling distance, the value of tractor skidding road density corresponding to that given value of the prehauling distance will be obtained.

Fig. 6 shows the relation between the prehauling distance by tractor-winch and the number of workers required per ha for log-pulling, carrying, and skidding road construction (but not containing workers for felling, delimbing and bucking operations because the number of those workers may not be significantly affected by the density and locations of tractor skidding roads). It shows the distance of prehauling, in other words, the density of tractor skidding roads which can minimize the total number of workers required for log-pulling, carrying, and skidding road construction. Needless to say, these values might be changed by types of TSRN.

Moreover, since the number of workers required is very variable depending on terrain and working conditions in logging sites, prehauling distance, skidding road density and the type of TSRN to minimize the number of workers required may also vary accordingly.

Table 4 shows the standard for selecting the most suitable and desirable type of TSRN, corresponding to different terrains and cutting systems.

This table and Fig. 7 indicate that for the terrain class of flat and gentle slopes (0 to 20% of gradient) the free route type of skidding without skidding road construction is adopted, and prehauling distance for log-pulling by the use of winch is made as short as possible, while skidding tractors are made to reach directly the site of stumps. On hilly slopes (20–30%), the semi-free route type of skidding should be adopted so that the dendritic road nets that would minimize the distance of skidding road is recommendable.

In this case, the skidding method or the layout of skidding roads should be planned to make the average prehauling distance by tractor-winch about 15 m. On steep and very steep terrains (over 33%), the skidding road

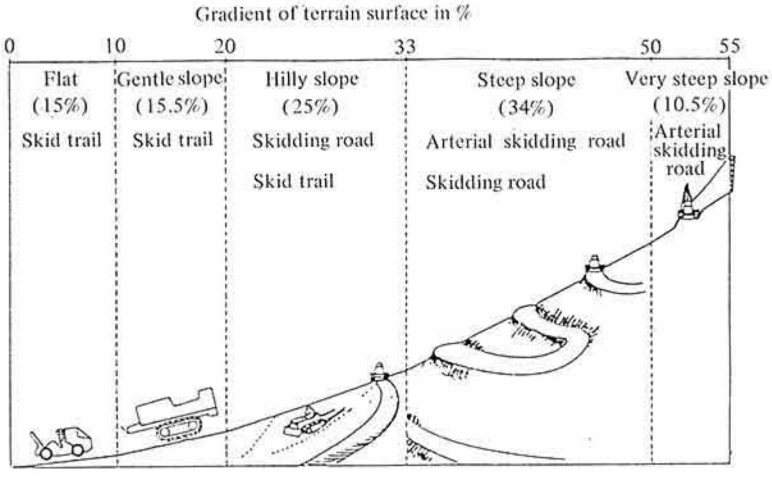


Fig. 7. Optimum skidding method corresponding to slope classes in Japan

net which consists of complex interlacing of higher grade skidding roads with lower grade ones should be adopted. The most suitable type of TSRN is the dendriform with arterial road nets for steep slopes (33 to 50%) and the herring bone type with arterial road nets for very steep slopes (over 50%).

2) *The process of planning TSRN for an actual logging site*

Fig. 8 shows a flow chart of planning TSRN. It is largely divided into the following four main steps: determination of planning area of forests, decision of the type of TSRN, design and route-location of skidding roads, and evaluation and comparison of skidding road systems.

All these planning works are carried out continuously and automatically by using a computer. The final output draws completely the most suitable skidding road nets and landing locations on a topographic map by only given input data such as terrain conditions (gradient of terrain surface, ground roughness and ground condition), working conditions (felling area, timber stands in-

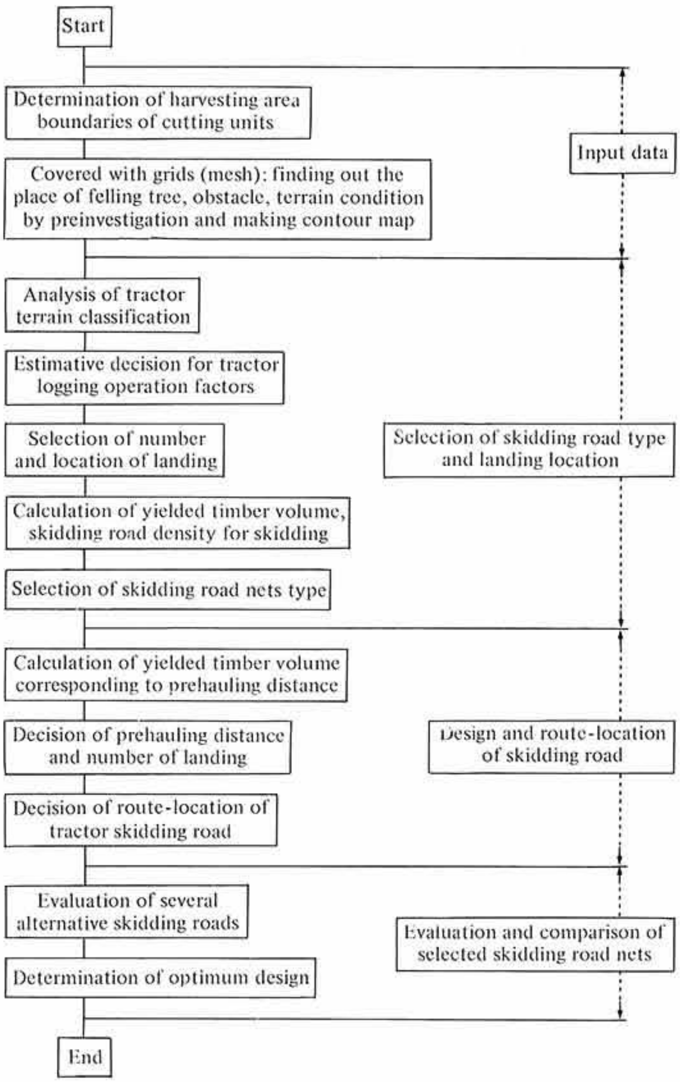


Fig. 8. Flow chart of planning tractor skidding road nets

ventory, distinction of man-made or natural forest, timber stock per ha, type of tractor, etc.) and others (location of existing forest roads and felling sites, shape of felling site, etc.).

Major interpretations developed from this planning system include: (1) the most suitable type of TSRN, (2) the most suitable prehauling distance for log-pulling by tractor-winch, (3) the most suitable density of tractor skidding roads, (4) the most reasonable location and the number of landings, (5) the ratio of arterial and branched skidding roads, and (6) road design map for TSRN.

Fig. 9 shows an example of the TSRN planned for an actual logging site by adopting the computer-aided planning method. If this method is to be practically applied to actual logging sites, the object of estimation should be clearly identified corresponding to the purpose, policy and conditions in a project area. But the most suitable layout of skidding roads can be selected from several comparable plans similarly obtained with varied objects of estimation. This method may be more objective and reasonable for the planning of TSRN, as compared with conventional ways.

Conclusion

The key to get satisfactory timber harvesting operations is good planning. Without a good plan, minimum cost and maximum profit in logging can not be expected. For a tractor logging system, the planning job is to select the most appropriate skidding system for harvesting timber, determine the route of skidding road, and select the locations of landing.

A complete planning system should include the evaluation of several alternative approaches to the best plan.

In this paper, the results of a research project designed to develop a computer program capable of determining the most suitable skidding method (the best number and location of tractor skidding roads and landings) in order to minimize the stand to landing harvesting cost for highly individual and different conditions in logging sites.

A series of computer programs, called

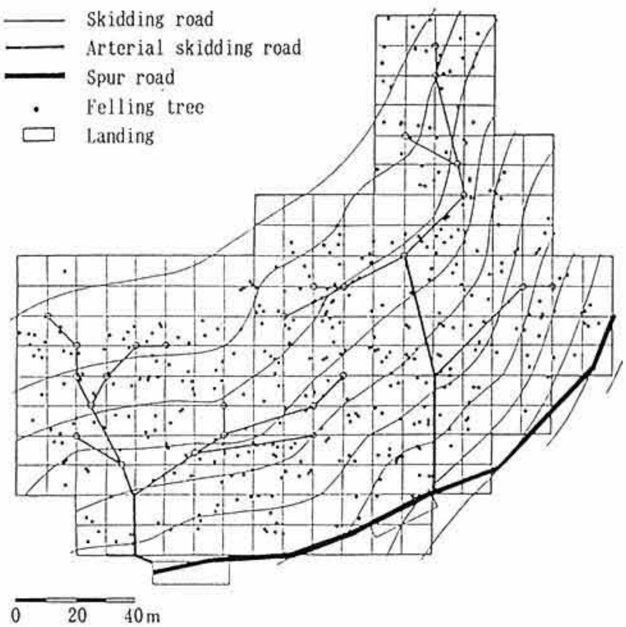


Fig. 9. Optimum arrangement of tractor skidding roads designed by the computer

TSRP, an acronym for Tractor Skidding Road Planning, is written in FORTRAN and is being run on ACOS-850 at the Agriculture Computer Center in Tsukuba. With a modest amount of modification and alteration, the program could be converted and applied to a desktop computer system.

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(Received for publication, Jan. 31, 1989)