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Determination of forest skid trail density in Caspian forests, Iran

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ABSTRACT: Calculation of Skid Trail Spacing (STS) is an important option to minimize the total costs of skidding. Construction of many skid trails increases the construction cost, it also results in more degradation on different levels in forests. On the other hand, by constructing less skid trails, winching cost will increase, and in many cases, the skidders will exit from skid trails. This research was carried out in four districts under management of Mazandaran Wood and Paper Industry Company with the aim of determination of Optimum Skid Trail Spacing (OSTS) for an HSM skidder. In this study, a continuous time study method to the nearest second with stop watch was used. The results indicated that the time modelling of winching was mainly affected by load volume and winching distance. By using the time modelling of winching, the winching cost is estimated and then by combining that with the skid trail cost graph, the OSTS graph is calculated. Finally, 95 meters is calculated as optimum skid trail density in this study.

Keywords: timber harvesting; winching; time study

The efficiency of logging operations in forest stands is largely dependent on the availability of adequate access through a transportation network, in terms of roads adjacent to wood storage areas and operational trails allowing machines to easily move inside the stand. Secondary forest roads, known as strip roads or skid trails, are a constructed infrastructure occasionally used to execute the tasks of a management plan. They are primarily intended for skidding or forwarding operations (Pentek et al. 2008). Forest utilization and logging in northern forests of Iran are very difficult and dangerous because of mountainous and sensitive ecosystem conditions (such as steep slope, high soil wetness, clay soil) and steep terrain. In order to enforce management standards, commercial utilization with maximum production and minimum degradation is required. With regard to principal utilization and higher efficiency, the application of available technology should be considered more than before. Primary wood transportation (i.e. transportation of logs from the stump area to roadside landings) is one of the most sensitive, time-consuming and difficult parts of forest utilization. That is why trained and skilful experts and labours, essential infrastructure (for instance: road, depot), advanced machines, high technical knowledge, data and information and accurate maps are highly needed (Sarikhani 2008). Primary wood transportation was done by a traditional method (animal skidding) until the 20th century. However, industrial wood logging systems have been introduced in order to increase the amount of logging from forest stands and improve the work efficiency (Zecic et al. 2005). In recent years in Iran, besides traditional methods wood extraction systems are combined with wheeled skidders and crawler tractors (Sobhani 1998). In northern forests of Iran, logging is done by wheeled skidders by planning skid trails and strip roads. If the skid trail density is high, forest damage and costs of skid trail construction increase. If the skid trail density is low, it may provide a poor coverage to extract in the forest stand. It also increases costs of road construction. So, we need an optimum skid trail density where the sum of costs would be on a minimum level. Optimum density and distribution of skid trails (where total road construction and skid trail construction are minimum) can play a very important role in reducing stand and soil damage. Furthermore, optimum density of skid trails can reduce costs (including: skidding cost + skid trail construction cost + stand and soil damage costs). An HSM wheeled skidder is one of the used machines in Iranian forests for logging, which works in a very similar way to Timberjack 450C skidder from the aspect of strength and working conditions. The understanding of different machine efficiency under available conditions is required for principal planning of annual forest logging. Considering sensitive conditions, determination of OSTS seems to be a critical option for the improvement of machine efficiency and reduction of stand and soil damage. Hence, this research was aimed at the determination of OSTS for an HSM skidder in forests under management of the Mazandaran Wood and Paper Company. There are no codified and comprehensive studies about the determination of OSTS for skidders, but in the following text you will see that a number of studies were done in order to determine effective factors on skid trail planning and estimation of wheeled skidder efficiency.

Baumgras et al. (1983) investigated the ground skidding in harvested stands in a region in Germany. The results indicated that the skidding cycle time was mainly affected by variables including skidding distance, weight of skidder, power of skidder, number of logs per cycle and time of choker setting. Lotfalian (1996) investigated the effects of skidding by TAF skidder on two soil types and gentle slopes in Kheirudkenar area located near the city of Nowshahr, north of Iran. The results showed that soil compaction increases if the traffic frequency increases. In this study, 21 skidder passes occurred, maximum soil compaction and rutting occurred in the twenty-first pass and the highest soil compaction was seen in CH (inorganic clays of high plasticity, fat clays) soil type, while rutting and log track in CL (inorganic clays of low plasticity, lean clays) soil type were higher and uphill skidding increased compaction more than downhill skidding. Adams (1997) investigated the effective factors on skidding from the stump area to roadside landings. Each factor was studied individually by the continuous time study method. The results showed that the variables including the size of logs, volume per cycle, skidding distance and average slope are the most important variables in a skidding phase from the stump area to roadside landings. Naeij Nouri (2004) investigated the necessity of the skid trail network and determination of the depot location in the forest management plans, and found out that optimum density, skid trail network and determination of the depot location for optimization of forest operations are the major issues in industrial logging in a ground skidding system because it will minimize the damage to forest sites and elements. Makineci et al. (2007) assessed the effect of skid trails on the forest soil in the *Abies* plantation in Turkey. The results indicated that ground skidding caused an extreme depression of vegetation cover of the forest floor. Also, forest soil compaction due to skidding resulted in increasing the weight of fine-grained soil (bulk density), depression of soil pores and depression of balanced soil water in skidding trails. Najafi (2007) investigated the time study for the HSM 904 skidder in the Mazandaran Wood and Paper Industry Company forests in order to obtain the mathematical productivity of machine model and cost of production. The results showed that the time of one skidding cycle was affected by skidding distance and the number of logs. However, it was not affected by the load volume and the slope of skid trail. Also, the net production rate and hourly cost considering the net production rate were 6.53 $m^3 \cdot h^{-1}$ and 41.1 $USD \cdot h^{-1}$, respectively. It also indicated that the time of releasing the winch cable and hooking and winching time increased due to untrained choker men and lack of coordination between them. So, training the choker men, changing the winch cable and the skidder operator cabin are needed in northern forests of Iran which leads to impressive improvement of productivity, safety and higher function of machines. Behjou et al. (2008) conducted the time study to determine the skidding capacity of a Timberjack 450C wheeled skidder in Caspian forests. They indicated that the skidding cycle time was mainly affected by skidding distance, winching distance and interaction between skidding distance and slope. The net production rate was 20.51 $m^3 \cdot h^{-1}$.

Rafiei et al. (2009) calculated the road construction costs and hourly costs for Timberjack 450C and HSM 904 skidders to determine Optimum Road Spacing (ORS) for a ground skidding system in Dalak Kheyl forest in the Hyrcanian zone. Also, the time study was done using a chronometer for skidding machines. The Matthews model was used to determine the optimum density of roads. The results indicated that the optimum density of forest roads for Timberjack 450C and HSM 904 skidders were 2–4 $m \cdot ha^{-1}$ and 3–5 $m \cdot ha^{-1}$, respectively. Lotfalian et al. (2011) studied the efficiency of Timberjack 450C wheeled skidder. Some factors including skidding distance, volume per cycle, slope, number of logs per cycle, winching distance, skidder establishment and manoeuvring time as well as time of each element in one skidding cycle were measured by using the time study. This time model was affected by independent variables of skidding distance and interaction between skidding distance and slope. The results showed that the net production rate and the unit cost, considering the net production in 980 m skidding distance, were 16.58 m^3 and 8.03 $USD·h^{-1}$, respectively.

Søvde et al. (2013) investigated the applicability of the Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic method in designing the machine trail layout. The optimization is done with a greedy constructive heuristic and a GRASP metaheuristic, and the results of the two solution techniques are compared. Both the greedy heuristic and the GRASP metaheuristic were examined for a semi-random terrain and a smooth cone-shaped terrain, and provided useable extraction trail layouts in terms of how a forest machine operates on slopes. The objective value of the solution found by the GRASP metaheuristic was 5.6% better than in the greedy heuristic in the semi-random terrain, and 2.3% better in the cone-shaped terrain. The result of this study showed that the GRASP metaheuristic is useful for finding feasible routes in the terrain, increasing efficiency. The method could be useful for planning feasible routes in the terrain, thereby increasing efficiency, or for acquiring a better estimate of the cost of terrain transport in price setting. Ozturk (2014) investigated the performance of Massey Ferguson farm tractor using the whole stem harvesting method in pine plantations in northern Turkey. The elements of the skidding work phase were identified, 30 cycles were recorded for this study and productivity of the tractor was determined by time measurements. Skidding time per cycle was directly related to tractor type, skidding distance and number of whole stems hauled, and inversely related to harvest intensity. Skidding productivity was sensitive to skidding distance, number of whole stems in a load and stem size. Skidding distance was 295 m on average; hourly productivity was 9.910 $m^3·h^{-1}$ for a skidding distance of 295 m. The total cost of Massey Ferguson tractor was calculated 22.98 $USD·m^{-3}$. Borz et al. (2014) assessed timber skidding efficiency in a mixed fir-beech stand undergoing group shelterwood cuttings. By performing the time study on 100 winching replications, which corresponded to 31 on-trail skidding replications, it was found that, in the case of all skidding operations, winching distance, skidding distance and number of logs forming a load were the most significant independent variables for the time consumption estimation. Delays (technical, operational and personal) accounted for 28% of the total skidding time, whereas in a delay-free skidding work cycle, winching and on-trail skidding accounted for 30 and 70% of skidding time, respectively. In the mean conditions (winching distance of 23.02 m, on-trail skidding distance of 1,037.32 m, volume of load of 7.12 m^3 and 3 logs per load), the net production rate was 12.65 $m^3·ha^{-1}$. All these studies confirmed that independent variables such as skidding distance, number of logs per turn and load volume are the most significant factors influencing the productivity and cost of logging. However, many studies about skidding have been done in Iran, but none of them addressed optimum skid trail spacing, therefore, the aim of this study was: to determine the OSTS to minimize total costs of skid trail construction and winching by representing a number as the space density pattern of skid trails in this study area. It also helps to make wood extraction economically, and subsequently to minimize the wood extraction costs.

MATERIAL AND METHODS

Study area. The study area was located in the Mazandaran Wood and Paper Industry Company forests, Mazandaran province, in the south of Sari city, which is covered by 200,000 ha and 73 districts, also it is the biggest forest management plan in Iran. In order to determine the STS for an HSM skidder, four districts were selected: including Arzep-hoon (compartment 5), Khalkheil (compartment 15), Khormandi Chal (compartment 12) and Nodeh (compartment 7), which are located between 52°50'20", 53°37'40"E longitude and 36°00'00", 36°27'30"N latitude. Table 1 shows the characteristics of the study area.

Table 1. Characteristics of the study area

District	Compartment number	Area (ha)	Stock ($m^3·ha^{-1}$)	Altitude (m a.s.l.)	Average slope (%)	Method	
						silvicultural	management
Arzephoon	5	64	274.4	650–800	0–30	selection cutting	uneven aged high forest
Khalkheil	15	48	220.61	620–800			
Khormandi chal	12	50	252.8	220–250			
Nodeh	7	46.5	250.2	400–450			

Methods. To estimate the winching time prediction model, some factors such as winching distance, mid-diameter and length of logs, time of all phases of winching, all kinds of delay time and log volume should be measured for each log individually. As the first step, the necessary and basic information, topographical maps and skid trail maps were collected from the forest management plan book. Then the authors visited the site of the study and collected field data. Winching time for 200 logs (i.e. in 95 cycles) in 10 days was recorded by the time study method. In each cycle, the length and mid-diameter of selected logs for winching were measured individually. To determine the log volume, Huber's volume formula (Zobeiri 2005) was used.

Subsequently, winching distance for each log from the stump area to skid trails was measured meter tape in each cycle. Continuous time study to the nearest second with stop watch for 200 logs was used during winching. All phases of winching including release of the cable winch, carrying the winch cable to the logs, choker setting and winching as well as different types of delays (such as technical, operational, and personal) were also recorded. The continuous time study was selected for two reasons. First, this method is proved to be more appropriate for scientific researches. Second, if some mistakes occur in parts of work, they can be removed easily from the work cycle because of being continuous in time.

After data collection, data based on regions was entered into MS Excel (Microsoft, Redmond, USA) separately in order to calculate the total winching time in the study area. After that, data sets were entered into the SPSS software (SPSS, Tulsa, USA) to create a regression model. In this model the total net winching time was considered as a dependent variable and effective factors during winching such as winching distance and log volume were considered as independent variables. As multivariable regression models are the only specific mathematical method for data analysis and estimation of the time-based model, it was developed in this study to determine the suitable model to predict winching time. In previous research Naghdi et al. (2004) also applied the method of multivariable stepwise regression analysis for time estimation. After estimating the optimum time based on the model which is calculated from the analysis of variance table by the step by step method, winching time at different densities of skid trails and subsequently winching cost can be measured. Winching cost at different distances and arithmetic summation of two total costs (they were mentioned before) were calculated in order to obtain the optimum density diagram. Matthews (1942) developed a model to define optimum road spacing based on minimizing the total cost of skidding and road construction from the viewpoint of a landowner. Major variables are removals per ha, skidding cost, road costs and landing costs. Many researchers have used and extended Matthews' model. Additional factors influencing optimum road spacing were identified by several researchers.

In fact, we intend to test whether this model is suitable for estimating the skid trail density or not. This research was performed in 2007.

RESULTS

There are 2 types of variables including fixed variables and dependent variables. Fixed variables that are fixed in each region (for instance: logging methods) and dependent variables such as skidding variables that are changing during forest operations (for instance: skidding distance). Dependent variables such as winching distance and log volume per turn were measured in this case. The terrain slope was not measured because the data set randomly included all classes of slope and the classification of slope did not solve any problems. So the slope factor was not measured in this case.

Calculation of skidding cost for HSM skidder

The skidding system cost contains machine cost and personnel cost. The machine cost contains fixed costs and variable costs. All types of fixed, variable, personnel costs for an HSM skidder were calculated to measure the skidding cost (Table 2).

Table 2. Summary cost information of skidding by a Timberjack HSM skidder

Parameter	Cost	Parameter	Cost
Purchase price (USD)	290,620	Depreciation (USD·yr^{-1})	163.47
Salvage value (USD·h^{-1})	29,062	Interest (USD·yr^{-1})	8.58
Economic life (h)	6–7*	Tax and insurance (USD·yr^{-1})	1.26
Tire price (USD·h^{-1})	4.27	Total fixed cost (USD·h^{-1})	173.31
Tire life (yr)	5	Total variable cost (USD·h^{-1})	152.93
Repair factor (f)	0.9	Total labour cost (USD·h^{-1})	14.34
System cost (USD·h^{-1})	389.51		

*annual: 800 working days

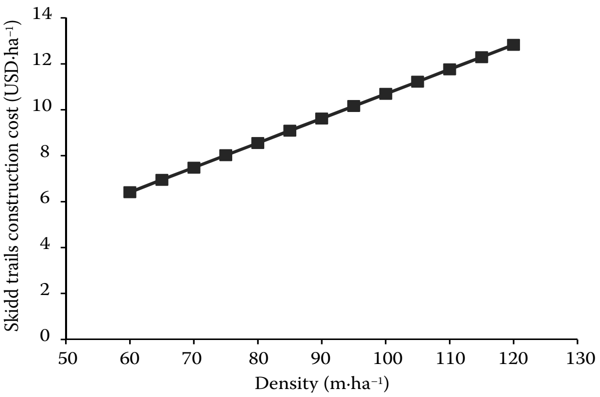

Fig. 1. Cost of skid trail construction

Calculation of skid trail construction cost

The available financial documents of the Mazandaran Wood and Paper Industry Company were used to estimate the cost of skid trail construction. The total cost of skid trail construction per kilometer is 106.95 USD, i.e. 0.106 USD·m^{-1}·ha^{-1}. In fact, the total cost of skid trail construction contains summation of planning cost, running cost, reclamation costs. The planning cost itself contains the cost of expert missions, labour cost, feeding cost etc. According to the company documents, the average running cost, which is referred to as the average skid trail construction cost, is 53.47 USD·km^{-1}. The skid trail reclamation cost contains reconstruction cost and all the services which prevent the forest from future environmental damage such as construction of water bars along the width of skid trails.

Fig. 1 presents the skid trail construction cost based on various skid trail densities. The diagram shows that the construction cost increases linearly when skid trail densities increase.

Estimation of winching time prediction model

The SPSS statistical program was applied to estimate the coefficient in the mathematical winching time prediction model. To this end, all data sets from field work were categorized in MS Excel. By applying the stepwise regression analysis, cloud distribution points of all data were depicted. As well, the relationship between effective factors and winching time was detected by Eq. (1):

$$Y = 31.24 + 1.91X_1 + 15.28X_2 \quad (1)$$

where:
Y – winching time (s),
X_1 – winching distance (m),
X_2 – load volume (m^3).

Table 3. ANOVA table for the regression equation according to winching distance and load volume

Factor	Sum of squares	df	Mean square	*F*	R^2	Sig.
Regression	212139	2	106069.51	54.88	0.36	0
Residual	380726.8	197	1932/66			
Total	592865.8	199				

Table 3 shows ANOVA for the winching time model. The coefficient of determination (R^2 = 0.36) shows that 36% of total variability is explained by the regression equation. The significance level of ANOVA shows that the model is significant at $\alpha = 0.05$.

Hence, using the above model and by fixing the load volume factor [by putting the mean load volume value (m^3) in the equation], winching times at different skid trail densities were calculated. A winching time-based model is used to estimate the cost of winching by Eq. (2):

$$Y = 31.24 + 1.91X_1 + 15.28X_2 \quad (2)$$

where:
Y – winching time (s),
X_1 – winching distance (m),
X_2 – load volume (m^3) per cycle of skidding.

For instance, the space between two skid trails is 166 m considering the skid trail density of 60 m·ha^{-1} according to Eq. (3):

$$10{,}000\ m^2/60\ m \approx 166\ m \quad (3)$$

In the stump area, 20 m (equal to tree height in the direction of skid trails) is subtracted from 166 m of two sides. As a result, skid trail spacing will be 63 m. Then, in the time-based model obtained from SPSS, X_1 = 63 m (the first variable or winching distance), X_2 = 1.11 m^3 (load volume) were calculated. Therefore, using the time-based model, with 60 m·ha^{-1} of skid trails and 63 m of skid trail spacing, the time obtained from the model will be 168.53 s. The amounts of a, b and c obtained from the model were 30.47, 1.897 and 15.28, respectively as follows from Eq. (4–6):

$$Y = a + bX_1 + cX_2 \quad (4)$$

$$Y = 31.24 + 1.897X_1 + 15.28X_2 \text{ and } X_2 = 1.11 \quad (5)$$

$$Y = 31.24 + 1.897 \times 63 + 15.28 \times 1.11 = 168.53\ s \quad (6)$$

Fig. 2a is a diagram of winching time at different skid trail densities that shows that the time consumption of winching decreases when the skid trail density increases.

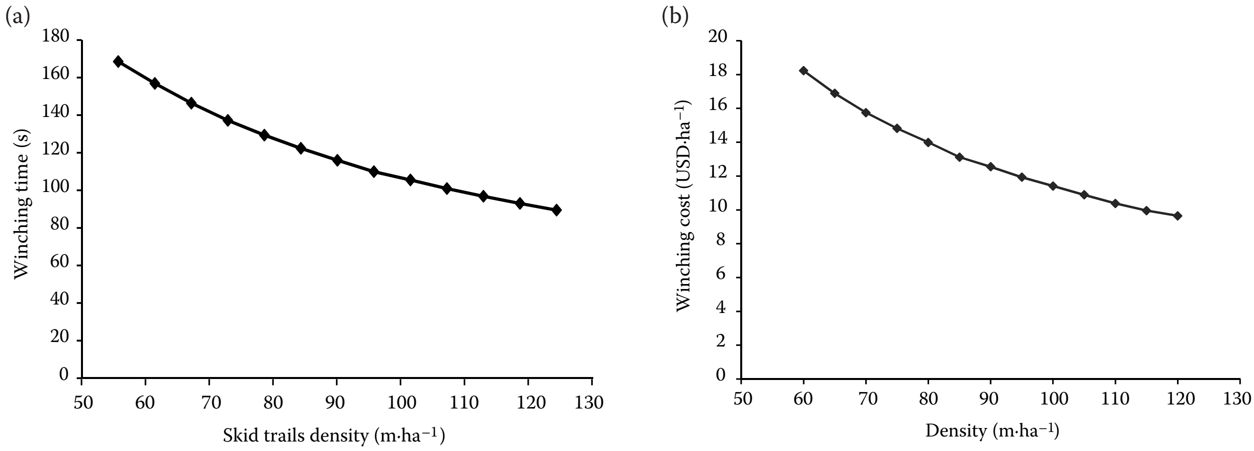

Fig. 2. Diagram of winching time (a), cost (b) at different skid trail densities

Estimation of winching cost by the time model

The cost value of the system (winching) 389.51 USD·h^{-1} was obtained, which was divided by 3,600 s in order to calculate the cost of the system (winching) per second per year. At this stage, the cost of winching can be calculated for different times and densities. For instance, after measuring the winching time by the model which was 168.53 s per 60 m·ha^{-1} skid trails, it was multiplied by the cost of winching (in seconds) to measure the cost of winching at a desired skid trail density Eq. (7).

$$389.51/3,600 \times 168.53 = 18.23 \quad (7)$$

If this procedure was repeated for 65–120 m·ha^{-1} densities of skid trails, the cost of winching for each skid trail density can be calculated. The cost of winching diagram at different skid trail densities according to above information and calculations is shown as follows.

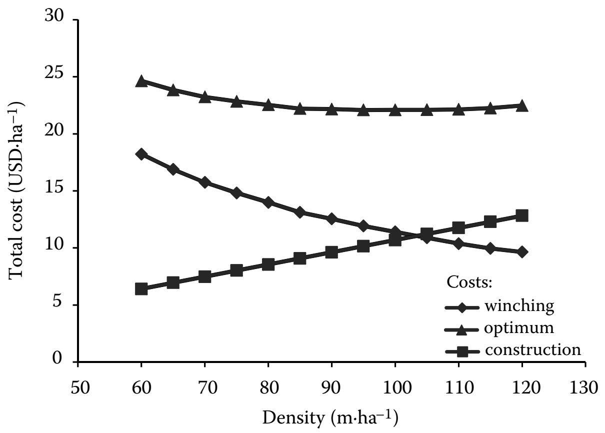

Fig. 3. Determination of optimum density of skid trails with respect to construction cost and winching cost

Fig. 2b shows the relationship between skid trail density and cost of winching. It indicated that the cost of winching decreases when the skid trail density increases.

Estimation of optimum skid trail spacing ranges

In order to estimate the OSTS ranges, both cost-time of winching and cost of skid trail construction diagrams were combined together. Subsequently, the mathematical summation of these diagrams was referred to as a diagram of summation costs of skid trail spacing.

Fig. 3 shows that by plotting the diagrams of summation of winching cost and cost of skid trail construction, optimum skid trail density can be obtained by finding a minimum point or a minimum range. OSTS was measured 95–100 m·ha^{-1}.

DISCUSSION AND CONCLUSION

Designing skid trails with optimum distribution and coverage can reduce the total cost of transportation. Also, it leads to a reduction of damage to natural sites, forest soil, residual stand and regenerations. In fact, skid trails are so important because they are the only way of wood extraction throughout the forest. So, the necessity of more consideration to designing skid trails with maximized coverage should be more emphasized. This research was conducted to determine the OSTS for an HSM skidder with the aim of reduction of total skidding cost, which is represented by appropriate skid trail densities in the study sites. The results of the time-based winching model, with time as a dependent variable, indicates that some factors such as winching and load volume have the highest influence on the total time of winching in the study sites, so that, with increasing each factor, winching time increases.

Skidding distance and load volume were the most effective factors (Adams 1977). Also, skidding distance was the most independent effective factor on skidding time. The mathematical sum of two diagrams of the cost of trail construction and winching cost showed 95 m·ha^{-1} as OSTS, which considering this density, the space density value of two skid trails with accounting 40 m height of trees from two sides, it is 106 m and without accounting 40 m height of trees, it will be 66 m, i.e. 33 m on each side (Baumgras et al. 1984). Moreover, the skid trail density for mini-forwarder and mini-yarder is 40 m·ha^{-1} and 140 m·ha^{-1}, respectively. He also stated that this amount can reduce the cost of production (total cost of trail construction and transportation) in forest harvesting and subsequently it can reduce the unit production cost. Moreover, the extent of occupied natural areas for log harvesting will be reduced, which will lead to lower soil compaction and subsequent erosion. The calculated value in this case study is close to the volume presented (140 m) by the Forests and Rangelands Organization. According to the principles of this Organization, the number of landings and designing parallel trails with minimum area and maximum coverage can prevent creating branch and diagonal forms of trails which cause heavy damage in natural areas and residual forest and regenerations (Shishiuchi 1993). On the other hand, direct trails without extreme turning and curves, as well as multiple landings for logging, are the optimum pattern to design the skid trails. This pattern, as well as a reduction of environmental damage, can result in a reduction of skidding costs. The low skid trail density causes high skidder traffic during skidding along the trails and it also causes the forest soil compaction (Raafatnia 2004). So, the effects of skidding on two forest soil types on a gentle slope were studied in Kheiroudkenar (in Noshahr city) for a TAF skidder. He found when the number of passes increases, soil compaction increases. The research was carried out in 21 passes and maximum soil compaction occurred during the 21st pass. Thus, skid trails with sufficient density can provide both minimum damage and reduction of skidding cost (Lotfalian 1996).

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