# Estimation of Turn Location Parameters for Cable Settings

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## ABSTRACT

Managers of cable yarding systems, confronted with inherently high owning and operating costs in a very competitive economic environment, need timely, inexpensive and accurate estimates of yarding production. Yarding time, and thereby production, depend on the location of the turn relative to the landing to which it must be transported. Among the important location attributes of a turn are distance and slope to the landing. For all of the turns on a setting the frequency distributions of these attributes are described by turn location parameters. Among the turn location parameters (TLPs) used by forest engineers are average yarding distance and average yarding slope.

The assumptions under which a relatively new class of TLP estimators has been developed are discussed in this paper. Recognition of these assumptions and full appreciation of the limitations thereby imposed on the use of the estimators are essential to judicious application of the methodology. Formulas and procedures are given for calculation of numerical estimates and, in order to clarify and illustrate their use, an example is given.

**Key Words:** *Average yarding distance, cable yarding, forest harvesting, logging engineering*

## INTRODUCTION

Forest engineers are under increasing pressure to examine an ever wider range of alternatives in harvesting systems, setting configurations and silvicultural prescriptions. Estimating cable yarder productivity when it is to be used under unfamiliar operating conditions is a difficult task. Fundamental to any such evaluation is information concerning the location of turns with respect to the landing. This information is usually summarized through the use of turn location parameters (TLPs). Average yarding distance (AYD) and average yarding slope (AYS) are among the more commonly employed parameters in this category. The fast accurate evaluation of harvesting alternatives relies upon the knowledgeable selection and use of these TLP estimators.

It should also be noted that these estimation procedures are fundamental to those layout optimization techniques that are applied to harvest units with centralized landings [8,11]. The comprehension and correct application of these contemporary design techniques presupposes an understanding of the basic concepts and procedures that follow.

New estimating formulas for TLPs associated with centralized landings on steep ground have been developed during the past decade. These new formulas when incorporated into easily implemented numerical procedures provide accurate parameter estimates for many steep ground cable settings. The variety of estimators available and the scope of their application are changing dramatically. Among these new estimators are those associated with the work of Peters [11], Donnelly [2], Garner [3], and Greulich [5].

Donnelly was the first to apply the coordinate area formula to TLP estimation in forest engineering. Donnelly's paper generally addresses settings located on flat terrain, and it was Garner who correctly extended Donnelly's numerical estimation procedure and Peters' average yarding distance formula to steep ground settings. Unfortunately Garner's paper was an internal report and not widely distributed. Good use could be made of these estimation techniques in both research and practice if they were more widely known. Indeed it would seem that many forest engineers are unaware of the advances that have been made in this field initiated by the seminal work of Suddarth and Herrick [12]. It is unfortunate, and not uncommon, to find continued reliance on erroneous results and estimation procedures given in Matthews' 1942 text, *Cost Control in the Logging Industry*. Increasing the awareness and use of these new estimation procedures by forest engineers is the primary purpose of this paper.

Parameter estimation accuracy is conditioned on the closeness with which the assumptions of the underlying model fit the conditions actually encountered on a specific setting. Some of the major factors determining the degree of model conformity with on-the-ground conditions are discussed. A

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computational algorithm is described and formulas are provided. An example illustrates some specifics of model application.

## ENGINEERING ASSUMPTIONS

The theoretical basis for this particular TLP estimation model, spanning three decades of developmental work by various researchers, has been described elsewhere [5]. In accordance with this theory it is required that to an adequate engineering approximation:

1. The boundary of the setting cut area be specified by one or more closed paths of connected line segments.

2. The route followed by any turn as it is yarded to a central landing be a straight line from the turn-building location in the setting cut area to the landing.

3. The individual turn locations across the setting cut area be described by independent, uniform probability distributions across the horizontal area of the setting cut area.

4. The ground surface of the setting cut area be described by, or by a portion of, the surface formed by lines radiating from the central landing to all points along the external yarding boundary.

These four engineering assumptions have been ranked in ascending order of risk. This subjective evaluation of risk attempts to incorporate both the criticality of an assumption and the probability of its violation in practice. None of these model assumptions are ever exactly met in practice and it is the task of the forest engineer to decide whether use of this particular model is generally appropriate to a specific situation.

The first assumption would seem to present little difficulty since any setting boundary may be approximated to the precision required by a sequence of straight lines. In practical terms however the time and cost of data collection done in the field will place a limit on the number of data points (hence line segments) that may be economically obtained. Settings that consist of many small irregular patch cuttings may present such data collection difficulties.

On very broken terrain the model reconstructed boundary may also for this latter reason fail to track the actual ground surface elevation. It can be anticipated in this particular situation that if difficulties are encountered with the first assumption then in all likelihood the fourth assumption will also be seriously violated.

With regard to the second assumption it is unlikely that the usual departures from a straight line yarding path encountered in the use of most cable systems will present a problem. There are some possible exceptions however such as the Cable-Lasso or zigzag monocable system [10]. The use of rub-trees or even long lateral yarding distances will not generally represent a significant deviation from the assumption. A final observation is that terrain of sufficient concave or convex curvature to cause a problem with this assumption would also imply a very serious violation of the fourth assumption.

It is generally safe to assume that the third assumption will be adequately approximated when clear-cutting in uniform stands of timber. Some caution is still warranted however even under those conditions. For example, on steeper ground it may be known that the trees will run when felled. A disproportionate number of turns will therefore be left along the edge of the standing timber or in the bottom of draws. The cable system employed may also change as the yarding progresses (e.g., from a high-lead to a gravity outhaul system as slope and external yarding distance increase) with possible attendant changes in the average number of logs per turn. Log payload per turn will vary on settings where deflection considerations actively constrain the hooking decision. Whenever the hooking rules predictably and significantly change turn payload across the setting this uniform distribution assumption must be carefully examined [1]. In most situations these variations in the number of turns per unit area can be accommodated by prudent partitioning of the setting into areas of relatively homogeneous combinations of log distribution and turn building conditions. Weighting procedures described in Donnelly's publication [2] can then be employed during the estimation process.

The fourth assumption can be met for any combination of landing location and setting cut area for which ground profiles from the selected landing location to all points along the external yarding boundary show generally uniform slope profiles.

Hence cut areas located on uniform side-hill slopes can be analyzed for any landing location on that same slope face. Cut areas that straddle a ridgeline formed by the intersection of two uniform slope faces (see example to follow) can be analyzed for any landing location along the ridgeline. A similar result extends to ravines formed by the intersection of two uniform slope faces. Cut areas located on the cone or funnel shaped ground often found at the nose of a ridge or the head of a canyon can also be analyzed but only for a landing located at the apex and toe of the slope in each respective case. In these last two cases it is also necessary that a sufficient number of line segments be installed around the cut area in order to adequately portray the curvature of the ground surface in those directions not radial to the landing.

If there is dead ground (an area crossed by the carriage or butt-rigging during the yarding cycle but from which no turns are removed) associated with a setting its surface profile is inconsequential to the analysis. It is only necessary that the actual yarded area of the setting have ground profiles that are approximately coincident with their corresponding segments of straight lines drawn from the landing to the external boundary.

## APPLICATION

Donnelly [2] gives a procedure for the use of the coordinate area formula in the calculation of average yarding distance. That procedure, in a more general format and with a minor sign modification, is repeated here. Formulas for the exact value of several TLPs of both theoretical and practical importance are also given.

The counter-clockwise path enclosing the setting (or partition) cut area consists of $N$ directed line segments. For each line segment a triangle is constructed using the beginning point, $(x_i, y_i, z_i)$, of the line and its ending point, $(x_i+1, y_i+1, z_i+1)$, as two of the vertices and the location of the landing, $(x_o, y_o, z_o)$, as the third. The horizontal area of each triangle is calculated by:

$$A_i = [1/2][(x_i-x_o)(y_i+1-y_o) - (x_i+1-x_o)(y_i-y_o)] \quad (1)$$

It is important to retain the sign attached to each of the $N$ areas so calculated. The total horizontal area of the setting or individual partition is then obtained by summing these individual triangular areas:

$$A = \Sigma A_i \quad (2)$$

This total area will have a positive sign attached to it if the formulas and procedures are used as described.

For each of the $N$ triangles the turn location parameter of interest, $TLP_i$, is calculated using the formulas provided in Table 2. The TLP of the setting or partition is then found as the area weighted average:

$$TLP = [1/A][\Sigma A_i TLP_i] \quad (3)$$

The formulas provided in Table 2, with the exception of that for $ES2_i$ which is presented here for the first time, may be found in previous publications [5,11].

Many forest engineers will want to write their own programs for the estimation of the parameters of particular interest to them. The publication by Donnelly [2] may be consulted as a detailed guide to the basic procedure. Donnelly employs an approximating formula for AYD in his program. The approximation is quite good but where slope is a significant factor an additional term for the elevational difference should be inserted into his AYD approximation formula. In the notation used here (see Table 2) the modified formula can easily be shown equal to:

$$AYD_i \approx [1/3][(2)(L^2_i,1+L^2_i,2)-L^2_i,3]^{1/2} \quad (4)$$

The right hand side of this formula is exactly the distance between the landing and the center of gravity of the triangle. Matthews [9] uses this distance as the AYD for triangular settings; but, as Donnelly unambiguously states, it is only an approximation.

Garner [3] has written and applied a similar program except that the exact formula for AYD is employed. These formulas and others are discussed in more detail elsewhere [5]. Particular consideration should be given to the use of approximating formulas when computational simplicity may be advantageous such as when hand-held calculators are to be used. It should be recognized however that the use of approximating formulas is an additional source of parameter estimation error. Some limited work with the approximations for AYD and AYS suggests that the error due solely to this source is generally below ten percent when compared to the exact formula.

**Table 2.** Formulas for turn location parameters.

The TLP$_i$ formulas that follow were derived using the procedures given in a previous publication [5].

Average yarding distance, AYD$_i$:

$$AYD_i = \frac{2}{3}\left\{\left[\frac{L_{i,1}+L_{i,2}}{4}\right]\left[1+\left(\frac{L_{i,1}-L_{i,2}}{L_{i,3}}\right)^2\right]+\left[\frac{2A_{i,a}^2}{L_{i,3}^3}\right]\left[ln\left(\frac{1+r_i}{1-r_i}\right)\right]\right\}$$

Average yarding slope, AYS$_i$:

$$AYS_i = \left[\frac{(100)(z_{i+1}-z_i)(L_{i,1H}-L_{i,2H})}{L_{i,3H}^2}\right] + \left[\frac{50}{L_{i,3H}^3}\right]\left[(z_i-z_{i+1})(L_{i,1H}^2-L_{i,2H}^2)+(2z_0-z_i-z_{i+1})(L_{i,3H}^2)\right]\left[ln\left(\frac{1+r_{i,H}}{1-r_{i,H}}\right)\right]$$

Expected square of the yarding distance, ED2$_i$:

$$ED2_i = \frac{1}{12}\left[3L_{i,1}^2+3L_{i,2}^2-L_{i,3}^2\right]$$

Expected square of the yarding slope, ES2$_i$:

$$ES2_i = \left\{\left[\frac{100}{a}\right]^2\right\}\left\{\left[aw\right]+\left[\frac{2a^2u-abv+b^2w-2acw}{(4ac-b^2)^{1/2}}\right]\left[tan^{-1}\left(\frac{2a+b}{(4ac-b^2)^{1/2}}\right)-tan^{-1}\left(\frac{b}{(4ac-b^2)^{1/2}}\right)\right]+\left[\frac{av-bw}{2}\right]\left[ln\left(\frac{L_{i,2H}^2}{L_{i,1H}^2}\right)\right]\right\}$$

Where in these formulas:

$L_{i,1}$ is the slope distance from the landing to the beginning point of directed line segment i.

$L_{i,2}$ is the slope distance from the landing to the end point of directed line segment i.

$L_{i,3}$ is the slope length of directed line segment i from beginning to end point.

$L_{i,1H}$, $L_{i,2H}$ and $L_{i,3H}$ are the corresponding horizontal distances between vertices of triangle i.

$z_0$, $z_i$ and $z_{i+1}$ are the elevations of the landing and turning points i and i+1 respectively.

For notational convenience the following definitions are also used:

$a = L_{i,3H}^2$

$u = (z_i-z_0)^2$

$r_i = L_{i,3}/(L_{i,1}+L_{i,2})$

$b = L_{i,2H}^2-L_{i,1H}^2-L_{i,3H}^2$

$v = 2(z_i-z_0)(z_{i+1}-z_i)$

$r_{i,H} = L_{i,3H}/(L_{i,1H}+L_{i,2H})$

$c = L_{i,1H}^2$

$w = (z_{i+1}-z_i)^2$

$A_{i,a} = \frac{1}{4}\left\{-\left[L_{i,3}^2-(L_{i,1}-L_{i,2})^2\right]\left[L_{i,3}^2-(L_{i,1}+L_{i,2})^2\right]\right\}^{\frac{1}{2}}$

**Table 1.** Estimates of turn location parameters for the setting.*

| Landing Coordinates | AYD[1] | AYS[2] | ED2[3] | ES2[4] |
|---|---|---|---|---|
| (1000, 1000, 1000) | 557.85 | 33.15 | 336254 | 1143 |
| ( 600, 1000, 920) | 347.83 | 30.22 | 141812 | 1229 |

1. AYD, average yarding distance
2. AYS, average yarding slope
3. ED2, expected square of the yarding distance
4. ES2, expected square of the yarding slope

* Exaggerated precision given for purposes of program verification.

It is always good practice to verify programs. One possible step in verification is the use of program data for which independently verified results are available. The input and results of the following example provide one such check. Every effort has been made to eliminate error in the example and anomalous results should be carefully checked.

Figure 1 shows the plan view of a small hypothetical cable setting together with a listing of the traverse turning points (TPs). Two alternative landings (TPs #22 and #23) are shown. It is assumed that turns are uniformly distributed over the cut area. The cut area is delineated by the three closed paths (CPs) of connected straight lines, CP1: (1 - 2 - 3 - 4 - 12 - 13 - 14 - 20 - 21 - 22 - 23), CP2: (5 - 6 - 7 - 8 - 9 - 10), and CP3: (15 - 16 - 17 - 18). CP3 delineates a small stringer of timber detached from the main stand and CP2 encircles an opening in the larger body of timber encompassed by CP1. With further regard to CP2 it is observed that TPs (#6 and #8) have been placed at the major break in the slope. Failure to place TPs at these locations would induce additional estimation error. In this particular case the error would be relatively insignificant because of the small area involved. There are no restrictions on the direction of traverse in the field but for purposes of data entry, and in accordance with the usual mathematical convention, the cut area should always lie to the left of the "line of traverse". As an example compare the direction of traverse for CP2 around an area to be excluded with that for CP3 which encircles an area to

be included. Connecting paths (dashed lines) of zero area, CP4: (4 - 5 - 10 - 11) and CP5: (14 - 15 - 18 - 19), tie the cut area paths into one continuous data entry sequence the coordinates of which are listed to the right of the sketch.

The two alternative landing locations along the E-W ridge-line were evaluated. The parameter estimates given in Table 1 were calculated using the procedure and exact formulas given in Table 2. During verification some minor deviations from the listed results should be expected if approximating formulas are used.

## CONCLUDING OBSERVATIONS

Predictive equations for yarding production commonly rely upon slope and distance as independent variables. These predictive equations are typically developed from time study data using linear regression. If this predictive equation is, or can be approximated by, a first or second order power series of distance and (or) slope then the formulas listed here are of potential utility. These predictive equations can be evaluated using parameters estimated for specific setting conditions in the manner just discussed and illustrated. Standard statistical procedures are applied in the evaluation of these predictive equations. A brief discussion of these evaluation procedures may be found in a previous publication [4].
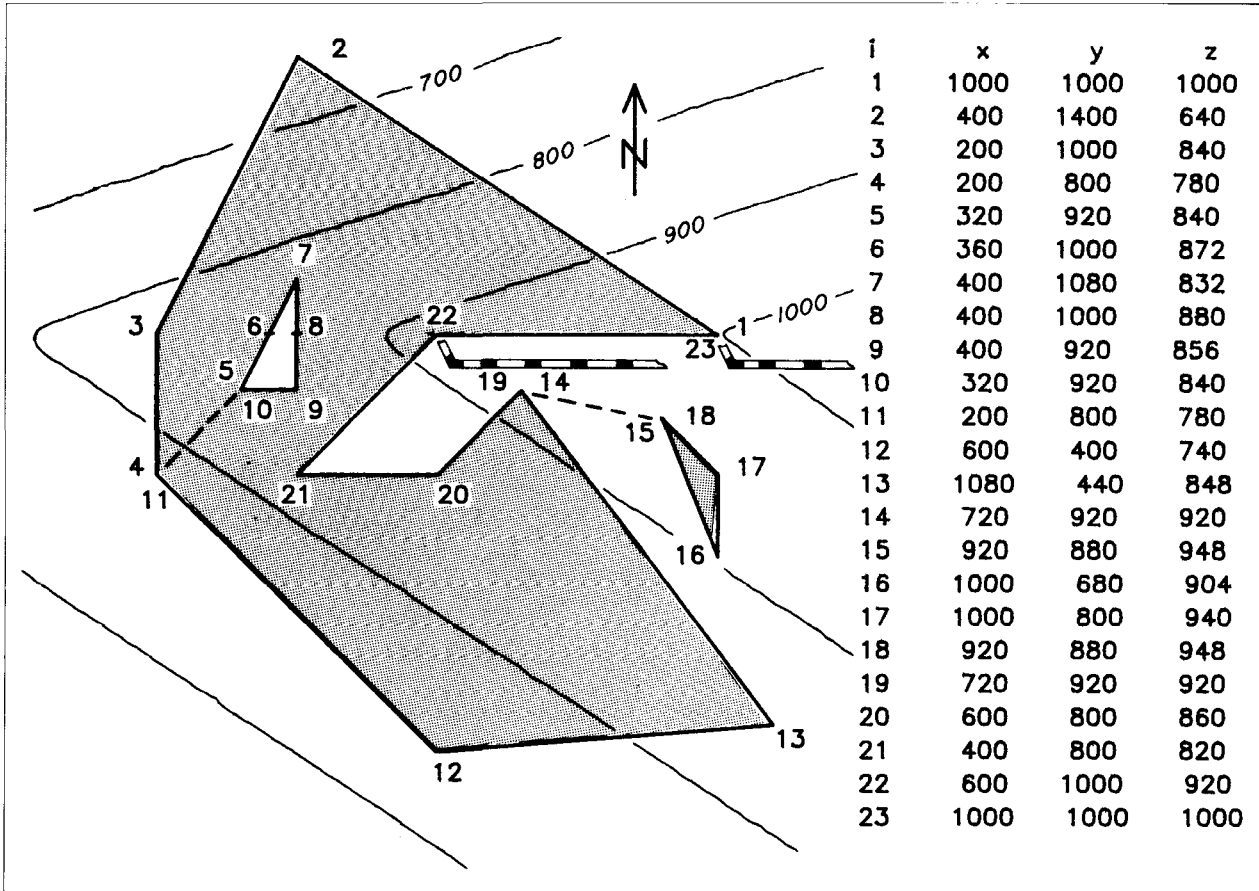
| i | x | y | z |
|---|------|------|------|
| 1 | 1000 | 1000 | 1000 |
| 2 | 400 | 1400 | 640 |
| 3 | 200 | 1000 | 840 |
| 4 | 200 | 800 | 780 |
| 5 | 320 | 920 | 840 |
| 6 | 360 | 1000 | 872 |
| 7 | 400 | 1080 | 832 |
| 8 | 400 | 1000 | 880 |
| 9 | 400 | 920 | 856 |
| 10 | 320 | 920 | 840 |
| 11 | 200 | 800 | 780 |
| 12 | 600 | 400 | 740 |
| 13 | 1080 | 440 | 848 |
| 14 | 720 | 920 | 920 |
| 15 | 920 | 880 | 948 |
| 16 | 1000 | 680 | 904 |
| 17 | 1000 | 800 | 940 |
| 18 | 920 | 880 | 948 |
| 19 | 720 | 920 | 920 |
| 20 | 600 | 800 | 860 |
| 21 | 400 | 800 | 820 |
| 22 | 600 | 1000 | 920 |
| 23 | 1000 | 1000 | 1000 |

**Figure 1.** Plan view of the example setting with coordinates of boundary traverse turning points.

While quite general in its assumptions this family of estimators is still somewhat restricted in application. It is the fourth assumption that is found to be most restrictive. Settings encountered on steep irregular terrain often cannot be realistically evaluated. There is however a class of TLP estimators with wider applicability [6,7]. These more general estimators only require that the setting cut area be everywhere visible from the landing. Because of the data and software requirements associated with these more general estimators their application is currently limited to the office environment.

In conclusion the family of TLP estimators discussed in this paper has numerous advantages. The basic assumptions of the model are easily understood and real-world conditions on many steep ground settings are acceptably approximated. A general formula exists for the development of parameters other than those given here and approximate formulas are available or easily derived in many instances [5]. A computational algorithm is easily written for either hand-held calculator or portable computer. Data entry is quickly accomplished either by keyboard and (or) use of a digitizer tablet. All these features make this class of TLP estimator the unsurpassed choice for immediate field evaluation of cable settings as well as a very attractive candidate for more general use by the forest engineer.

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**NOTE**

An experimental, undocumented executable program for IBM compatible PCs is available to interested readers. Developed for classroom use this program calculates the parameters given in Table 1 and permits easy modification of the setting boundaries and landing location for comparison of design alternatives. Send a formatted high density (1.44 Mbyte) $3\frac{1}{2}$" diskette together with a self-addressed pre-paid mailer to the author.