

Transportation Networks in Forest Harvesting: Early Development of the Theory

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Abstract: A solid theoretical basis for the design of transportation networks in forest harvesting has been under development for at least a century. The genesis of this theoretical development can be found in the research of early European academics. At the close of the nineteenth century graduates of European universities carried these concepts to America. There, as faculty in newly established, turn-of-the-century forestry programs, they inculcated a new generation of foresters with an appreciation for economic efficiency in harvesting transportation and the theoretical basis for its achievement. Through the first half of the twentieth century this theory most notably continued its development in America. The last fifty years however have seen development of the theory proceed apace in Europe and America with increasing contributions from Asia. Significant early milestones in the development and dissemination of forest transportation network theory are identified and an attempt is made to connect these seminal events and to place them in the context of lesser-known, yet pertinent, research publications both within and without the field of forestry.

The economic conduct of forest harvesting operations has long been the primary objective in the construction and maintenance of the forest transportation network. In 1901 Bernhard Eduard Fernow, then Dean of Cornell's forestry college, addressed a meeting of leading American engineers of that turn-of-the-century era with following words:

The first task of the forester, then, in beginning the management of a forest property is to provide cheap and efficient means of transportation for the removal of a bulky crop, of which much is inferior, and if possible to so arrange this harvest that it may be made gradually, logging over the same area for a number of years.

And Dr. Carl Alwin Schenck, Director of the Biltmore Forest School, in his text on forest policy (1911) more succinctly asserted:

Indeed, it might be stated that forestry is essentially a problem of transportation.

What then is the transportation network? For the forester engaged in harvest planning the

transportation network leads from the tree standing in the forest to the millyard gate. Various modes of transport with intervening transshipment points are the norm; for example, logs are cable yarded to a central landing where they are loaded onto trucks destined for the mill. Transportation modes in current use range from ox teams to helicopters, from logging trucks to railroad cars, from log-rafts to ocean-going freighters. Ground transportation is conducted over minimally prepared, seasonally restricted surfaces, as well as paved all-weather highways. Transshipment points can be landings along truckroads, log sorting and reload yards, ports of embarkation and debarkation, and a variety of other locations where the logs are transferred from one conveyance to another. Equipment used to effect log transfer at transshipment points ranges from front-end and heel-boom loaders, to portal cranes and A-frames. For today's forester at least part of the network is usually in-place and quite typically consists of mainline forest-roads and public highways. Despite this existing infrastructure accessing the forest stand through the economic location, construction and use of spur-roads, landings and skid-trails still confronts the forester with a

problem in network design. It is a problem that the forester frequently addresses, and he does so with notable success, relying upon practical rules and procedures born of theoretical results that have been under development for more than a century.

Dr. Johann Karl Gayer, Professor of Forestry Utilization at the University of Munich, published the first edition of his textbook on forest utilization in 1863. It became the recognized standard in this field for German foresters and was translated into English in 1896 by Professor William Rogers Fisher of the Royal Indian Engineering College in Coopers Hill, England. Sir William Schlich, first director (1885-1905) of the forestry section at Coopers Hill, added this translation as a fifth volume to his *Manual of Forestry*. This volume then became the standard reference on forest utilization in England and America for many years. Indeed Dr. Schenck, who received his doctorate from the University of Giessen and was assistant to Sir William Schlich, relates that he prepared many of his lecture notes for American students at Biltmore from Sir William Schlich's *Manual of Forestry* (Schenck 1955). The economic transport of wood is a major theme of this volume where we read:

The great influence which the available means of transport has on wood-prices is well known, and has been already referred to. All unwise economy in providing good means of transport depresses prices, and improvement in this respect should be one of the first objects of the forest owner.

Every intelligent forest owner will endeavour to reduce the cost of transport from his forest. The forester therefore lays-out new roads, improves old ones, regulates floating channels, constructs slides, sledge-roads or tramways; establishes depots on the banks of streams and canals and at railway stations.....

Elers Koch, a 1903 Yale graduate, notes that

there were no American forestry textbooks and that the five volumes of Schlich's *Manual of Forestry* were the "standby" (1998). Dean Fernow, a graduate of the Forest Academy at Muenden, also praises this collection and other German-language books that even more specifically address the various means of forest transportation (1913). He mentions Braun (1855), Kaiser (1873), Muhlhausen (1876), Foerster (1885), Runnebaum (no date), and Stoetzer (1903). (The surnames and dates are the only reference information provided by Fernow.) These works were published during a period when location theory was rapidly developing in Germany; a development that had begun during the first half of the nineteenth century.

The rigorous development of economic location theory had its origin in early nineteenth century Germany led by the work of Johann Heinrich von Thunen and Johann Georg Kohl (Mosler 1987). During the latter half of that century the preeminent theorist and practitioner in the economic location of railroads was Professor Carl Friedrich Wilhelm von Launhardt at the Polytechnic of Hannover. His ground-breaking work in the optimal location of railroad networks originally published in German only became generally accessible to English and American engineers in 1900 with the English-language publication of *The Theory of the Trace*. In spite of this text and earlier publications in prominent German-language engineering journals Professor Launhardt's work in location theory was not widely recognized. Many of his original, and published, concepts and analytical developments were rediscovered and popularized at a later date by subsequent location-theory economists such as Professor Alfred Weber of the University of Heidelberg in Germany and Professor Tord Palander of Uppsala University in Sweden. Pinto (1977) would subsequently attribute much of this neglect, "to imperfect lines of communication among the various subdisciplines in this field of

study".

It must be confessed here that only a small portion of the German forest transportation literature of that era has been examined by the present author for citations of Professor Launhardt's work. Judging from the English-language publication record it does seem quite likely that most American and British foresters were unaware of Professor Launhardt's publications. No mention of Launhardt was found in the writings of Schlich, Fernow or Schenck examined by this author. Likewise no evidence has been found that American civil engineers, including railroad engineers, were cognizant of Launhardt's work. A premier civil engineering reference of that period (Turneaure 1909) does not even discuss the economics of railroad network development. The section on highway construction does give an example of selecting the "best" road network joining three towns. Launhardt's principle of nodes or principle of junctions, had the author been aware of these principles, could have been introduced in the context of this example but in fact the proffered solution is quite simplistic, devoid of any real economic analysis. (Both of these principles were published by Launhardt in 1872 and repeated in his text of 1900.) Wellington (1898) offers a somewhat better evaluation of railroad branch line location but he still comes nowhere close to the generality or level of economic rigor to be found in Launhardt's text.

It is evident that Fernow, Schenck and Pinchot, European-educated foresters, instilled an abiding awareness of forestry transportation issues among their students and colleagues. Their alumni were quick to answer the need for American textbooks in this critical area of forestry practice. Professor Ralph Clement Bryant, the first graduate of Fernow's forestry program at Cornell, published his textbook on logging in 1913; it was followed by a second edition in 1923. Professor Nelson Courtlandt Brown, a 1908 graduate of Yale's Master of

Forestry program, published the first edition of his textbook, *Logging - Transportation*, in 1936. These textbooks seem somewhat exceptional for their time in that they provided an extensive bibliography, something lacking in many publications of that era. Both of these textbooks were heavily oriented toward practical issues of forest transportation system planning and execution. Only minor attention was given to the theoretical aspects of transportation network development. Continuing in the spirit of Schlich's *Manual of Forestry* the primary contribution of these textbooks was to maintain the focus of American foresters on the singular importance of transportation related issues and their engineering solution.

American education in transportation engineering strongly emphasized the applied physical sciences; its secondary attention to economic decision making included little that would be appropriate to network analysis. In 1911 this deficiency began to be appreciated with the publication of Taylor's provocative text *The Principles of Scientific Management*.

The necessity for and applicability of Taylor's time studies procedures in forestry operations was immediately perceived (Braniff, 1912). At the thirteenth session of the Pacific Logging Congress in 1922 James W. Girard, logging engineer with the United States Forest Service (USFS), addressed the on-going issue of economic rationalization of the forest transportation network. His detailed time studies would now permit for the first time the scientific examination of the trade-off between two modes of forest transportation. In his presentation he states:

The amount of railroad which should be constructed, or the distance apart that the spurs should be constructed can be definitely determined, provided that there is a reliable estimate of the timber and the cost of railroad construction can be closely determined.

The skidding distance that gives a skidding cost which, when added to the cost of railroad construction results in the lowest total cost per thousand for both skidding and railroad construction, shows the distance apart that the railroad spurs should be.

Girard (1949) writes that he started his work on the economics of forest transportation in the period 1909 - 10. By 1919 Girard had started the data collection and analysis that would eventually contribute to the exceptionally thorough USFS study published by Bradner *et al.* in 1933.

In their 1933 publication Bradner *et al.* present not only the results of their extensive analysis of harvesting operations data but they also detail procedures for its practical application in the design of forest transportation networks. Of particular interest is their calculation of average skidding distance, also known as the average yarding distance (AYD), to a continuous landing. When evaluating the AYD on a setting with uneven timber distribution they recommend the use of a weighted mean distance. They also modify the direct surface distance from the felled tree to the landing to adjust for the actual distance followed during tractive skidding. Operationally they provide a table for the "most economical distances between railroad spurs" given conditions of slope, volumes per acre, tree size, season of the year, and skidding mode (tractor or horse). Theirs however was not the first published work to employ these concepts. Curves giving the economic skidding distance under various operational conditions had previously been published by Krueger (1929). Krueger also adjusted the straight-line skidding distance for the winding path actually followed by the tractor as did Hughes in his 1930 publication. Hughes, in addition, discussed the use of weighted AYD's for production estimation.

Also in 1933 Axel Brandstrom's very well-known study of logging costs in the

Douglas-fir region was published. In this study and also in an earlier preview of this work (Munger and Brandstrom, 1931) the analyst correctly calculates the AYD for a circular cable setting with a central landing. Robert Worthington, a student working in conjunction with this project writes in his 1932 master's thesis: "Costs for different yarding distances are based on the general rule that the average distance of haul within a yarding circle is approximately 2/3 of the average distance to the outside boundary".

It was a long-standing practice of early forest engineers to describe the layout of their cable yarding operations in terms of its external yarding distance (the radius of the yarding circle created if working from a central landing on level ground). Consider for example the 1910 description given by James O'Hearne, logging engineer with the English Lumber Company of Mt. Vernon, Washington, which is quite typical. In describing the use of the Lidgerwood skidder he writes: "We have been clearing up a circle of a little over 800 feet radius at each setting". In estimating expected costs during the planning phase of a cable logging show it was necessary to calculate the AYD, and forest engineers of the 1930's were clearly using the correct formula for an approximately circular setting. The origin of this formula, as then used by foresters, is unknown but it is noted here that Launhardt (1900) had developed and applied essentially the same formula in his analysis of railway rates. Unfortunately, the absence of a recognized theoretical basis for this formula within the forestry profession was soon to lead to a lengthy regression in this particular component of network theory.

The publication of Professor Donald Maxwell Matthews' 1942 textbook, *Cost Control in the Logging Industry*, was a milestone in forest transportation network analysis and design. The first five chapters of Matthews' text gives the reader a basic introduction to the scientific

collection and preparation of logging related data together with some relevant economic principles and their application. The book then turns to its major topics: the economic selection of equipment and road standards, the optimal location of roads and landings, and the influence of slope on these decisions. As a compendium of forestry related network design problems and as a source of inspiration to subsequent researchers in this field Matthews' text has yet to be surpassed. In truth however, many of the problems presented by Matthews had been posed and even solved by previous researchers. In addition, the theoretical basis for much of its network analysis has been successfully challenged by subsequent articles in the referred literature. One such topic has been that of how to calculate the exact AYD for a setting.

Matthews, using an erroneous equal-area argument, derived the AYD for a circular setting with a landing located at its center. His result, in direct conflict with previous forest engineering practice, went unchallenged in America for 22 years. In 1964 Suddarth and Herrick, in derivations consistent with Matthews' assumptions, corrected his formula. They also present the correct formula for a central landing located at an acute vertex of a right triangle, and, by area weighting they extend this formula to a rectangular area with a corner landing. While generally recognized as the first publication to present these results to English speaking foresters they were not the first to develop and publish the correct formulas. In fact Professor Ulf Sundberg's 1953 paper presents essentially the same results. Larsson (1959) attributes the analytical development in Sundberg's paper to G. Almqvist. Larsson's 1959 paper is, itself, a mathematical *tour de force* in forest network design. His stated objective was:

.....to determine that combination of the road spacing, the road standard, the general structural layout of the road system and the

method of transportation, which results in the minimum sum of the cost of transportation in the timber area, the cost of transportation on the road, the cost of loading and unloading, and the total cost of road per unit transported from the timber area under certain definite assumed conditions.

Generally unknown to other researchers his results are occasionally rediscovered; e.g., road shortening (Peters and Nieuwenhuis 1990), and simultaneous road standard and spacing optimization (Yeap and Sessions 1989). It is noteworthy that Larsson also unknowingly rediscovers and presents a previously published result, Launhardt's "principle of the junction". Parenthetically it is also noted that as late as 1999 Professor Beckmann continued to attribute this particular principle to Professor Palander.

Most of Matthews' network development problems, though not all, assume a boundless, homogeneous ground surface covered by a uniform stand of timber. The 1978 publication by Peters represents perhaps the culmination of this line of inquiry. Bryer (1983) suggested that Peter's model might be changed to permit a more efficient pattern of settings - a general line of thought that was in fact explored quite early on in the modeling of market areas in location theory (Puu 1997). By the 1970's the character of the network design problem facing American foresters was changing. Most of the mainline forest roads had been long established and logging was now moving into the second-growth timber lining these existing routes. There was growing interest in the economic design of logging spurs that would branch off these existing mainlines. These spurs were being developed to reach smaller cutting units frequently comprised of irregularly shaped settings in non-uniform timber stands and often located on terrain with broken slopes.

In 1978 Dennis Donnelly of the USFS

published an exceptionally useful procedure for the calculation of the AYD for a setting of irregular shape on flat ground with a central landing. This innovative procedure employs the coordinate area formula to calculate the weighted AYD. Previous use of the coordinate area formula in weighting procedures can be found in geography (Blair and Biss 1967) and geology (Hall 1976) where formal derivations are given. In 1979 Garner, using Donnelly's weighting methodology and his modification of the AYD formula given by Peters (1978), presented the correct procedure to calculate the AYD under some common ground-slope conditions. Building on the results of Peters, Donnelly, and Garner, Greulich (1987, 2000) went on to derive and apply formulas for additional setting parameters including average yarding slope and average external yarding distance. The theoretical advances presented by Peters and Donnelly led to a procedure for the optimal selection of a single landing location for irregularly shaped settings encompassing non-uniform timber stands on flat, homogeneous terrain (Greulich 1991, 1997). Work now continues on optimizing branch location and road standard selection for spurs leading to multiple landings (Greulich 1995, 1997, 1999). Research potentially relevant to future developments in the optimization of multiple landing locations has been done by Professor Okabe of the University of Tokyo and is to be found in the book *Spatial Tessellations*. Professor Okabe has also derived and applied the exact formula for the distribution function of what would be the distance from the central landing to a randomly located turn in a setting described by a polygonal figure (Okabe and Miki 1984, Okabe 1987). More recent work, also of possible relevance to forestry operations, has been done by Professors Okabe and Miller (1996). Certainly the text by Okabe *et al.* (2000) should be consulted by all researchers involved in transportation network theory. Readers are cautioned however that the authors of this latter publication are unaware of work done by forest

researchers which in some instances is well in advance of the material presented in the text. A similar lack of familiarity with location theory work done by foresters is found in transportation science (*vide* Francis and White 1974, Love *et al.* 1988, Drezner 1995), location theory (*vide* Puu 1997, Beckmann 1999), and urban studies (*vide* Larson and Odoni 1981, Vaughan 1987).

The historical development of network theory in forestry spans a hundred years and numerous countries. It is a history that continues to be shrouded in uncertain origins and discontinuities in the research record. Many early publications are found with few, if any, citations of previous work; there is also a general lack of familiarity with concurrent theoretical developments in other academic disciplines.

Despite these deficiencies a very early and unflagging interest in the improvement of forest transportation systems has resulted in numerous theoretical advances. Most of these advances have gone unnoticed outside of forestry. Even within the American forestry profession there continues an inability to adequately identify significant contributions, most notably those made in non-English language journals or low-distribution foreign publications. It is clear that the cautionary note of Professor Beckmann (1984) is equally pertinent to all researchers, not only economists, who would work in network theory:

Many are the attempts by general economists to pick out some tempting problem in location theory and present a quick solution - so there - often in ignorance of better treatments already published in the location theoretical literature. Thus anybody can get into the act and many have done so.

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