AN ABSTRACT OF THE DISSERTATION OF

Sang-Kyun Han for the degree of Doctor of Philosophy in Forest Engineering presented on February 21, 2011

Title: Managing Woody Biomass Transportation for Improved Biomass Economics

Abstract approved:

Glen E. Murphy

With rising fuel costs and enhanced environmental concerns, the use of renewable energy has been steadily considered and widely expounded as a solution to the challenges of global energy security and climate change. The use of woody biomass, in particular, has received considerable attention for energy production due to the potential availability of large volumes from fuel reduction thinning operations and healthy forest restoration plans. However, woody biomass utilization is not as economically attractive as fossil fuel due to the high production and transportation costs compared to the relatively low market values of these materials. Therefore, identifying or developing cost effective production and transportation systems has become an economically critical issue to expand biomass utilization. In woody biomass production, the transportation of wood raw materials from the sources to the conversion facilities is the largest single component of production costs for many suppliers around the world. Therefore, small increases in transportation efficiency could significantly reduce the overall production costs. The purpose of this study was to provide new knowledge which leads to improvements in the economic feasibility of using woody biomass for energy through reductions in transportation costs.

This dissertation:

- Developed prediction models to estimate the travel times including terminal (loading and unloading) times to haul woody biomass from non-forest sources to conversion facilities in western Oregon and determined the effects of off-forest road classes on transportation times and costs. The travel time prediction model developed was shown to be a good predictor for travel time through a validation procedure. The average percent difference between actual and predicted travel times was only 6 percent.
- Developed a computer model, named BIOTRANS, to estimate the biomass transportation productivity and cost and evaluated the effects on transportation costs of different truck configurations, transported material types, and travel route characteristics. Different truck configurations and transported material types significantly affected transportation costs. A 4 axle truck and single trailer was the most cost efficient hauling configuration for the conditions studied and shavings have 30 percent higher trucking costs than other material types.

- Developed an optimization model to solve a truck scheduling problem for transporting four types of woody biomass in western Oregon. For an actual 50-load order size, the truck scheduling model produced significant improvements in solution values within 18 seconds. The average reductions in transportation cost and total travel time were 18% and 15%, respectively.
- Reviewed collaborative management systems and described the potential implementation of collaborative transportation management in the woody biomass transportation industry.

MANAGING WOODY BIOMASS TRANSPORTATION FOR IMPROVED BIOMASS ECONOMICS

by

Sang-Kyun Han

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APPROVED:

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Sang-Kyun Han, Author

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CONTRIBUTION OF AUTHORS

I would like to recognize the considerable contribution of Dr. Glen Murphy on all the papers cited in this dissertation. His contribution included conceptual formulation, study design and reviews for each chapter.

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CHAPTER 1

GENERAL INTRODUCTION TO DISSERTATION TOPIC

1.1 LITERATURE REVIEW

1.1.1 Background

With rising fuel costs and enhanced environmental concerns, the use of renewable energy has been steadily considered and widely expounded as a solution to the challenges of global energy security and climate change. For instance, U. S. President Obama has commented that renewable energy could supply 10% of the nation's electricity by 2012, rising to 25% by 2025 (Obama and Biden 2009). Hydroelectricity, wind power, solar power, geothermal power, and biomass are considered as current renewable energy sources.

Biomass energy has recently become an attractive suitable alternative to fossil fuels in the United States due to a sustainable supply chain of energy sources. The use of biomass for energy generation could also contribute to waste utilization and pollution alleviation as well as energy conservation. Biomass has recently become the single largest source of renewable energy by surpassing hydropower and now supplies over 3% of the total energy consumed in the United States (Perlack et al. 2005).

The use of woody biomass, in particular, has received considerable attention for energy production due to the potential availability of large volumes from fuel reduction thinning operations and healthy forest restoration plans. The amount of forest biomass available for bio-energy conversion was estimated to be 368 million dry tons annually (Perlack et al. 2005). In addition, when forest biomass sources are combined with agricultural biomass sources, it would be possible for biomass to support 30% of the energy provided by fossil fuel (Perlack et al. 2005). However, woody biomass utilization is not as economically attractive as fossil fuel due to the high production and transportation costs compared to the relatively low market values of these materials. Although the U.S government provides substantial government subsidies for biomass to become a viable alternative, high production and transportation costs are still economic barriers to the widespread utilization of woody biomass for energy production (Rummer 2008). Therefore, identifying or developing cost effective production and transportation systems has become an economically critical issue to expand biomass utilization.

Transporting wood raw materials from the sources to the conversion facilities is the largest single component of production costs for many suppliers around the world. In past studies, transportation costs account for about 25 to 50 percent of delivered costs depending on hauling distance, load bulk density and moisture content of delivered materials (Ronnqvist et al. 1998, McDonald et al. 2001, Halbrook and Han 2005, Pan et al. 2008). McDonald et al. (2001) reported that transport costs represent about half of the delivered cost of wood raw materials in the southern USA. Pan et al.

(2008) studied the production cost of small-diameter (less than 5 inches) trees for energy. They reported the transportation cost represented 47 percent of the total cost and found it was the largest component of the total system costs. Especially in low value material, such as forest biomass, transportation costs are the critical component to be economically managed to reduce the total production costs. Research on transportation systems by Ronnqvist et al. (1998) is also relevant to the economics of bio-energy production. They suggested small increases in efficiency of transporting woody material from sources to energy plants could significantly reduce the overall production costs. There is considerable interest by forest industries worldwide in decision support systems (Cossens 1993, Palmgren 2001, Murphy 2003), equipment configurations (Sinclair 1985, Webb 2002), and road-truck interactions (Douglas et al. 1990) that can lead to reductions in overall transport costs and improve the utilization of wood.

1.1.2 Transportation equipment for woody biomass transportation

Chip vans are the most cost efficient method for transporting forest biomass around the world (Rawlings et al. 2004). Chip vans usually need some specific forms such as solid panels to prevent the loss of small woody particles and the possum belly in the underneath of the trailer to increase the potential payload of trailers (Angus-Hankin et al. 1995). However, these advantageous configurations often result in limited accessibility of chip vans on the forest roads because they have greater off-tracking, lower clearance, and higher center of gravity compared to conventional log trucks. Conventional chip vans, can, therefore, only be used on forest roads which have been designed and constructed with wider curves than those designed for the stinger-steered log trucks which are typically used for log transportation in the forest. For these reasons, the development of new equipment configurations has received considerable attention in woody biomass transportation.

Sinclair (1985) described a container system to recover woody biomass from mountainous terrain. He found that this system has good potential to haul chunks and short logs from landings and roadside debris accumulations in the forest. Webb (2002) introduced the log/chip B-train vehicle which was capable of hauling both chips and logs and could improve chip and log truck utilization. Rawlings et al. (2004) described a roll-off trucking system that has a straight frame truck configuration in which modular containers are “rolled” onto and off of the straight frame truck by means of a truck-mounted hydraulic winch and a hook. They tested this system in two different harvesting sites and found that a roll-off trucking system significantly improved both accessibility to more forest residues and economic efficiency of the recovering process. In recent years, the U.S. Forest Service has designed a stinger-steered chip van. It combines features from a regular logging trailer and a cargo container and can access the same forest roads as a conventional logging truck. This is considered to be a better alternative than constructing or reconstructing forest roads for conventional chip vans since there are lower investment costs associated with converting existing trailer systems to stinger-steered chip van configurations.

1.1.3 Travel time models for forest roads

Travel time per unit distance is mainly influenced by the travel speed. Travel speed on a particular road segment is determined by several road factors such as horizontal and vertical alignments, road widths, surfacing characteristics and other road properties. Load size and truck characteristics will also influence the travel speed but, within an optimum range of load sizes, the influence would be small (Groves et al 1987). Several forest transportation studies have examined the relationship between travel times and road classes and also developed models to predict truck travel times and transportation costs based on road classes (Byrne et al. 1960, Groves et al. 1987, Moll and Copstead 1996, Pan et al. 2008).

Byrne et al. (1960) in their classic logging road handbook quantified the effects of road design variables such as grade, alignment, road width, and surfacing on hauling productivity and costs from US forests. The field work for this publication, often referred to as BNG, was carried out in 1947. The trucks on which it was based have changed substantially over the past half century. Therefore, there has been interest in determining the accuracy of BNG and if necessary, improving the travel time component of BNG. Jackson (1986) tested BNG to predict log truck travel speeds in three different locations in Western Oregon on favorable grades and curves. They found that BNG for favorable grades steeper than 16 percent overestimated travel times compared to observed travel times. In favorable grades less than 16 percent, however, it was a relatively good predictor of travel times.

Moll and Copstead (1996) reported a comparison of BNG with observed travel times and two computer based vehicle performance simulation packages, OTTO and TRUCK. Log truck travel times were observed at three National Forest sites-the Sequoia in California, the Tongass in Southeastern Alaska, and the Chattahoochee in Georgia. They found that BNG predictions were closer to observed times than software predictions for most conditions. The differences between predicted and observed data were not as great for BNG as for OTTO. TRUCK produced overly high speeds with extremely wide range for Sequoia conditions.

Groves et al. (1987) investigated the travel times of articulated logging trucks along varying classes of road in Tasmania, Australia. They also developed a road classification systems based on road functions and conditions. Using this system, prediction model was developed to estimate travel times over any specified route for both unloaded and loaded travel. They found that loaded and unloaded travel times were strongly related to their road classes ($R^2 > 95\%$). In model validation by comparing actual and predicted travel times per trip, they found that the prediction model sufficiently estimated travel times within a maximum error of 6%.

Pan et al. (2008) investigated productivity and cost on four fuel-reduction thinning treatment units in Arizona. Time studies were applied to develop cycle time regression equations for harvesting machines including feller-buncher, skidder, loader, grinder, and chip vans. A prediction model for travel time was developed for three different road types and one material type; hog fuel. They found that the transportation distance on various road types positively affected the hauling cycle time. The regression coefficients suggested that given the same distance, spur road distance had the greatest effect on cycle time, while the influence of highway was less.

Most of the past investigations were related to conventional log trucks. The literature lacks information about the effects of road classes on transportation costs for chip vans to carry woody biomass from sources to conversion facilities.

1.1.4 Trucking cost models

Trucking industries face different input prices, product characteristics, truck configurations, geographical characteristics, firm size, and driving practices. Therefore, it is difficult to obtain current estimates of costs for particular independent owner/operators. Understanding of transportation cost structure through simulations of cost models can help identify possibilities for efficiency gains that may lead to increased profits or decreased costs (Casavant, 1993). In particular, a productivity and costing model can be used to plan and optimize woody biomass transportation operations by allowing the user to vary truck configurations, haul routes and other haul cost parameters. A number of truck costing models have been developed both within and outside of the forest industry.

Taylor (1988) described a spreadsheet-based truck costing model (TRUCKAAI) that was developed by the New Zealand Logging Industry Research Association. The costs of owning and operating trucks were combined with user-supplied productivity data (average haul distance, average payload, number of trips per day, etc.) to provide a trucking rate ($ per tonne-trip).

In Canada, the Forest Engineering Research Institute of Canada (FERIC) developed a log transportation cost model, programmed using Visual Basic (Blair, 1999). The costs of constructing and maintaining forest roads as well as the costs of owning and operating the trucks were incorporated into the model. The program allows the user to specify a haul fleet and haul route, and then analyze the costs of the specified haul system. In this paper, the model was tested for log transportation from the stump to the mill in Alberta, CA. He also performed cost sensitivity analysis and evaluated the key cost elements affecting log transportation costs.

Trimac Consulting Services also created a computerized activity based model for commercial grain trucking in Western Canada (Trimac Logistics Ltd., 2001). This computer model permitted the user to estimate total transportation cost based on realistic transportation data input by users and to explore the impact of various operational conditions and data assumptions on costs.

In the USA, Berwick and Dooley (1997) developed a truck cost model for transporting agricultural products such as barley, corn, oat, wheat, and soybeans in North Dakota. The truck cost spreadsheet model was designed using Microsoft Excel. The model allowed the user to estimate trucking costs for a variety of truck configurations, product characteristics, trip conditions, and input prices. The spreadsheet model was constructed with six linked sheets; trip characteristics, fixed cost, variable cost, trailer, cost summary, and sensitivity pages.

In the Pacific Northwest, My Fuel Treatment Planner (MyFTP) based on Microsoft Excel, was created by the USDA Forest Service (Fight and Barbour, 2004). This model mainly estimated the production and hauling costs associated with forest fuel reduction treatments and also included potential revenues from these treatments. In this paper, they also proposed the development of a new trucking cost model for hauling chips due to limited accessibility of chip vans compared to conventional log trucks.

1.1.5 Truck scheduling models

Planning for woody biomass transportation is considered to be a complex problem because it has multiple supply and demand points, multiple material types, multiple truck and trailer configurations, and multiple time periods. Currently, woody biomass truck fleets are typically scheduled and dispatched by transport planners based on their local knowledge and experience. For small-sized truck fleets, transport planners can handle the organization of their trucking routes adequately without scheduling aids. With increasing fleet sizes and supply and demand points, however, they often create inefficient and poorly organized truck schedules which may result in long working hours for each truck and long waiting times at loading and unloading places. To improve log trucking efficiency, a number of optimal truck scheduling and dispatching systems have been developed.

In New Zealand, Murphy (2003) developed a 0/1 integer linear programming truck route scheduling model and tested it in two medium-sized New Zealand forest companies. They found that truck fleet size could be reduced by 25 to 50% in two forest companies. Substantial cost savings were also identified. Bixby and Lee (1998) devised a branch-and-cut algorithm for solving integer linear programming (ILP) formulations of the truck route scheduling problem. This program was performed on 14 real instances supplied by Texaco & Transportation, Inc. They found that the optimal schedule produced significant cost saving for the company and greater job satisfaction for drivers due to more balanced work schedules. However, the application of these ILP methods often fails for large-scale problems because computation time dramatically increases with problem size (Contreras et al. 2008).

Traditionally, several heuristic approaches have been developed to solve larger problems in reasonable time (Weintraub et al. 1996, Sun et al. 1998, Nanry and Barnes 2000, Lin et al. 2009). Although heuristic approaches may not always guarantee that optimal solutions have been found, they have been the focus of a large number of researchers because of their high efficiency and capability of problem solving especially for large and complex problems.

Weintraub et al. (1996) developed an operative and computerized system, named as ASICAM, based on heuristics rules to support daily truck scheduling decisions for the Chilean log transport sector. It could be used on any personal computer and ran for about three minutes on a PC 486 for larger problems. They tested this program in eight of the largest forest firms in Chile and found average reductions of 31% in truck fleet size and 13% in average working hours and operational costs.

Andersson et al. (2008) developed the decision support system, RuttOpt, which was developed for scheduling logging trucks in the forest industry in Sweden. The system was made up of a number of models. The first module was the Swedish road database NVDB, which provided detailed road information and computed distances between locations. The second module was an optimization program that was based on linear programming and standard tabu search methods. The third module was a database storing all relevant information. RuttOpt was tested in a number of case studies in Sweden. They found that the system can be used to solve large case studies and produced reductions of 30% for truck fleet size and 8% for the total distance traveled.

Nanry and Barnes (2000) applied reactive tabu search algorithms to solve the pickup and delivery problem with time windows. In this program, three different methods to search neighborhoods were applied; single paired insertion (SPI), swapping pairs between routes (SBR), and within route insertion (WRI). In order to validate the effectiveness of this algorithm, the results were compared with those reported by previous studies that tested the same problem using different tabu algorithms. They found that this approach improved the solution quality and efficiency compared to previous studies.

Lin et al. (2008) applied simulated annealing heuristics to truck and trailer routing problems and found that simulated annealing is competitive with tabu search in identifying optimal solutions. In addition, the algorithm was very efficient as it takes less time to obtain the best or near-best solutions.

Contreras et al. (2008) applied the ant colony optimization (ACO) metaheuristic to efficiently solve large and complex forest transportation problems. The solutions from the ACO algorithm were compared with those obtained from a commercially available mixed-integer programming (MIP) solver. The ACO solutions were competitive with the MIP solution, but the ACO algorithm solved problems much faster than the MIP solver.

Most of the past forest to mill truck scheduling and dispatching models were developed for conventional log trucks and very few examples in the literature deal with woody bioenergy transportation. One of the few examples is by Eriksson and Björheden (1989) who presented a linear programming model for solving a fuelwood transportation problem.

1.2 RESEARCH OBJECTIVES

The ultimate objective of this study is to provide new knowledge which leads to improvements in the economic feasibility of using woody biomass for energy through reductions in transportation costs. More specific objectives included:

- Determining the effects of road classes on transportation times and costs based on transportation routes used to haul forest biomass in the western Oregon.
- Developing prediction models to estimate the travel times including terminal (loading and unloading) times from sources to conversion facilities for forest biomass.
- Developing a computer model to estimate the transportation productivity and cost for woody biomass.
- Evaluating the effects of different truck configurations, transported material types, and travel route characteristics on transportation costs.
- Developing an optimization model to solve a truck scheduling problem for transporting woody biomass in western Oregon.
- Reviewing collaborative transportation systems in trucking industries.
- Describing the potential implementation of collaborative transportation management in the woody biomass transportation industry.

1.3 ORGANIZATION OF THIS DISSERTATION

This dissertation is a comprehensive study of an important transportation operation in woody biomass supply chains, namely the transportation of woody biomass residues from sawmills to energy facilities or export terminals. The overall goals of the study were to improve the utilization of woody biomass and enhance the competitiveness of woody biomass as a source of renewable energy.

The dissertation has been written in a manuscript format and is composed of four distinct manuscripts. Each manuscript is designed to stand alone, resulting in some duplication of background information and results. The manuscripts are ordered in a logical sequence that allows the reader to broaden existing knowledge on woody biomass transportation. Our improved knowledge should lead to increasing transportation efficiency in the trucking industry and improving the utilization of woody biomass for energy production. The following is a synopsis of each chapter, corresponding research questions, and significance.

Chapter 2 introduces the prediction models to estimate the travel times including terminal (loading and unloading) times from sources to conversion facilities for forest biomass and summarizes the effects of road classes on transportation times and costs based on transportation routes used to haul forest biomass from a range of sites in western Oregon. The road class system is mainly defined in terms of radius of curvature and road grade to explain the effects of vertical and horizontal alignments in the highway. The study is limited to chip vans travelling on off-forest roads.

Chapter 3 describes the cost structures in woody biomass transportation from saw-mills to conversion facilities (energy or pulp) or to export harbors in western Oregon. The goals were to develop a computer model to estimate the transportation productivity and cost for woody biomass and also to evaluate the effects of different truck configurations, transported material types, and travel route characteristics on transportation costs. The truck costing model should provide the user with useful information for trucking companies that need accurate truck cost information to negotiate desirable rates and determine appropriate transportation performances.

Chapter 4 introduces an optimization model to solve a chip truck scheduling problem for transporting woody biomass in western Oregon. In this chapter, the problem is limited to transporting by-products (chips, hog fuel, sawdust, or shavings) from saw-mills to conversion plants (energy or pulp) or harbors for export. A simulated annealing approach is used to obtain optimal solutions within reasonable times. To test the quality of solutions, our algorithm was analyzed for several different scenarios in a medium size scale problem which included 40 mills, 20 plants, 75 loads per day, 4 product types, 75 trucks, and 6 truck-trailer configurations. A comparison was also made for an actual 50-load schedule.

Chapter 5 reviews collaborative transportation systems in trucking industries and introduces the benefits of CTM based on studies that were external to and within forest industries. This chapter also discusses how the leadership of the coalition can be assumed, how participants in a coalition are selected, and how to share cost savings between precipitants for the general establishment of a collaborative transportation coalition In addition, we describe the potential implementation of CTM in the woody biomass transportation industry.

Chapter 6 is a concluding chapter that conceptually integrates the results and brief discussions of the four previous chapters, and describes the potential contributions made with this study. In addition, this chapter introduces current research limitations found in our study and discusses further research direction.

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CHAPTER 2

PREDICTING THE LOADED TRAVEL TIMES OF ON-HIGHWAY WOODY RAW MATERIALS HAULING TRUCKS FOR IMPROVED FOREST BIOMASS UTILIZATION

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2.1 INTRODUCTION

Biomass energy has recently become an attractive suitable alternative to fossil fuels in the United States due to high fossil fuel costs (Arola and Miyata 1980). The use of biomass for energy generation could also contribute to waste utilization and pollution alleviation as well as energy conservation. Biomass has recently become the single largest source of renewable energy by surpassing hydropower and now supplies over 3% of the total energy consumed in the United States (Perlack et al. 2005).

Forest residues, agricultural residues, and urban waste are considered to be huge potential biomass resources for energy production in the US. Forest harvesting and mill residues, in particular, have received considerable attention for energy production due to the potential availability of large volumes from fuel reduction thinning operations and healthy forest restoration plans. The amount of forest biomass available for bio-energy conversion was estimated to be 368 million dry tons annually (Perlack et al. 2005). In addition, when forest biomass sources are combined with agricultural biomass sources, it would be possible for biomass to support 30% of the energy provided by fossil fuel (Perlack et al. 2005). However, biomass utilization is not as economically attractive as fossil fuel; high costs of biomass collecting, processing, and transporting to energy conversion facilities currently presents an economic barrier to utilization of forest biomass for energy production. Rummer (2008) comments that it would require substantial government subsidies for biomass to become a viable alternative. Finding the best ways to lower biomass production costs has become an economically critical issue to expand biomass utilization to partially replace fossil fuels.

The U.S. Departments of Energy (DOE) and Agriculture (USDA) have recommended that higher biomass production costs could be partially offset by lower wildfire fighting costs. Wildfire costs could be lessened by reducing fuel sources through biomass harvesting (Perlack et al. 2005).

Given that the high cost barriers of collecting and processing the biomass can be overcome transport costs will also need to be addressed. Transporting wood raw materials from the sources to the conversion facilities is the largest single component of production costs for many suppliers around the world. McDonald et al. (2001) reported that transport costs represent about half of the delivered cost of wood raw materials in the southern USA. Pan et al. (2008) studied the production cost of small-diameter (less than 5 inches) trees for energy. They reported the transportation cost represented 47 percent of the total cost and found it was the largest component of the total system costs. Especially in low value material, such as forest biomass, transportation costs are the critical component to be economically managed to reduce the total production costs. Ronnqvist et al (1998) note that research on transportation systems is also relevant to the economics of bio-energy production. They suggested small increases in efficiency of transporting woody material from sources to energy plants could significantly reduce the overall production costs.

Chip vans are the most cost efficient method for transporting forest biomass around the world (Rawlings et al. 2004). Chip vans usually need some specific forms such as solid panels to prevent the loss of small woody particles and the possum belly in the underneath of the trailer to increase the potential payload of trailers (Angus-Hankin et al. 1995). However, these advantageous chip van configurations often cause limited accessibility on the forest roads because they have greater off-tracking, lower clearance, and higher center of gravity compared to conventional log trucks. For these reasons, chip vans may have different transportation requirements, such as road designs and travel routes, and performance measures, such as travel speeds and payloads.

The effect of road design on transportation costs has long been recognized (Matthews 1942, Byrne et al. 1960, Groves et al. 1987). Transportation costs per unit distance are mainly influenced by the travel speed. For example, if travel speed increases, costs per unit distance will decrease. Travel speed on a particular road segment is determined by several road factors such as horizontal and vertical alignments, road widths, surfacing characteristics and other road properties. Load size and truck characteristics will also influence the travel speed but, within an optimum range of load sizes, the influence would be small (Groves et al 1987). Several forest transportation studies have examined the relationship between travel times and road classes and also developed models to predict truck travel times and transportation costs based on road classes (Byrne et al. 1960, Groves et al. 1987, Moll and Copstead 1996). Byrne et al. (1960) quantified the effects of road design variables such as grade, alignment, road width, and surfacing on hauling productivity and costs from US forests. Groves et al. (1987) developed prediction models to estimate truck travel times and transportation costs using eleven road classes based on road functions and conditions in Tasmania, Australia. They found that loaded and unloaded travel times were strongly related to their road classes ($R^2 > 95\%$). However, most of the past investigations were related to conventional log trucks. The literature lacks information about the effects of road classes on transportation costs for chip vans to carry woody biomass from sources to conversion facilities.

This study was performed to identify the effects of road classes on transportation times and costs based on transportation routes used to haul forest biomass in western Oregon. The specific objectives were to define road classes which reflect the performance of chip vans and develop prediction models to estimate the travel times including terminal (loading and unloading) times from sources to conversion facilities for forest biomass. The study was limited to chip vans travelling on off-forest roads. Our improved knowledge should lead to better management of trucking fleets, improved road design and reduced transportation costs to improve the utilization of wood raw materials for energy production.

2.2 STUDY METHODS

2.2.1 Data collection

2.2.1.1 Transportation data

Transportation data used in this study was obtained from Terrain Tamers (TT) which is a trucking company located in Dillard, OR. The company has been involved in hauling logs and lumber as well as chips around western Oregon and southwestern Washington, but now is primarily focusing on chip hauling. They use approximately 70 trucks in their operation and most of their truck fleet consists of 3 axle double vans (load capacity: 105,500 lbs, total trailer length: 64 ft) and 4 axle vans (load capacity: 102,500 lbs, total trailer length: 53 ft). Travel routes are based on Oregon Transportation Route Map #7 provided by Oregon Department of Transportation (ODOT). Map #7 represents allowable truck lengths, weights and heights for each road in Oregon. Terrain Tamers requires its drivers to record performance information for each trip. Trip information included pick-up and drop sites, travel times, loading and unloading times, and down time. The travel information was organized and stored in TT's computer system.

For this study, data relating to all of the loaded trips occurring between May 2007 and May 2008 were provided by TT. During this period, the company transported a range of raw materials such as hog fuel, chips, shavings, or saw dust from the mills or lumber companies to energy or pulp conversion facilities or ocean export terminals in western Oregon and southern Washington. No hog fuel or chips were delivered into energy plants from harvesting sites.

A total of 107 transportation routes were utilized. Terrain Tamers provided travel data in the form of sources (pick-up site), final conversion facilities (drop site), transported materials, number of trips, average travel time, average loading time and average unloading times for each of these 107 routes. Information on the type of loading system at the pick-up site and unloading system at the drop-off site was not available. Nor was information available on waiting time due to queuing at the loading and unloading sites. Loading and unloading times were sorted by types of wood raw materials. Weighted average loading and unloading times were calculated based on the number of trip records.

2.2.1.2 Road geometry data

Road geometry data were obtained from ODOT. For this study, ODOT provided two GIS shape files, a horizontal curve shape file and a vertical curve shape file, for all highways based on Oregon Transportation Route Map #7. In both shape files, each road was divided into segments which ranged from 1 to 10 miles according to ODOT’s survey points. However, segment lengths for each road differed between the two shape files due to different survey procedures for horizontal versus vertical curves. The vertical curve shape file provided the beginning milepoint of each curve, the curve type, and the percent grade for each segment. The horizontal curve shape file included length of the curve, degree of the curvature, total curve angles as well as beginning and ending milepoints for each curve. Curve radii were calculated using the horizontal curve information.

Difficulties for further analysis arose due to different length of segments between the two shape files. To combine both vertical and horizontal information based on the same segment length, attributes in each GIS shape file were transformed into Excel spreadsheets. Visual Basic programming in Excel allowed the combining of both vertical and horizontal information into a new Excel file based on same segment length. Analysis was limited to roads travelled by TT chip vans in western Oregon and southwestern Washington. This road geometry file, which contained 30,243 segments, was used to evaluate the road class for each road segment.

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2.2.2 Road classification system

A combination of specific road characteristics, specific vehicle characteristics, specific driver characteristics, specific weather conditions, and specific traffic conditions might be expected to affect truck performance. However, trying to take into account all of the potential variables could lead to a very complex prediction model that in practice has large errors associated with it and performs poorly (Groves et al. 1987). A simple road classification system, which includes explicitly defined road variables, may better explain the truck performance and produce more accurate prediction models for truck travel time. Therefore, only road design parameters were used in our road classification system and the effects of truck, driver, traffic and weather characteristics were ignored. The road classification system was mainly defined in terms of radius of curvature and road grade to explain the effects of vertical and horizontal alignments in the highway (Table 2.1). These parameters are implicitly efficient to investigate limited travel routes for long trailers such as chip vans.

Table 2.1 Road classification system

	Road grade	Radius of curvature			
		Straight (> 1000 ft)	Rolling (700 – 1000 ft)	Mountainous (300 - 700 ft)	Sharp (< 300 ft)
Highway	Steep (> 5%)	(1)*	(2)	(3)	(4)
	Fair (3 – 5 %)	(5)	(6)	(7)	(8)
	Good (0 – 3 %)	(9)	(10)	(11)	(12)
	Downhill (< 0%)	(13)	(14)	(15)	(16)
Urban road		(17)			
Freeway		(18)			

* (1) to (18) refer to classes of road for this study.

In the road classification system used, the radius of curvature in the road segments was divided into four different classes (Level, Rolling, Mountainous, and Sharp curves) following the guidelines for highway geometric design provided by American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 2004). The division of road grade (Steep, Fair, Good, and Downhill) was derived from the truck performance models reported by Douglas et al. (1990). Two additional road classes, urban and freeway, were added to give a potential total of 18 different classes in this road classification system (Table 2.1). However, some of these classes did not occur in this study. The segment lengths of each road class were summed to give a single value for each road class for each of the 107 routes (Table 2.2 and Appendix).

2.2.3 Data analysis

Data analysis was performed using Statistical Analysis System (SAS) (SAS Institute Inc. 2001) and Statistical Package for the Social Sciences (SPSS) (SPSS Inc. 1998). Multiple regression analyses using ordinary least squares estimators were used to develop the prediction models that estimate the travel times as well as loading and unloading times. The prediction model for travel times was based on travel distance (miles) for each road classes. Prediction models for loading and unloading times were developed based on the type of material transported (hog fuel, chip, shavings, and sawdust) and the configuration of trailers used (single and double). In all of the prediction models, normality tests, residual plots, and Durbin-Watson test were used to determine violations of the Gauss-Markov assumptions and a forward selection method was used to search for a suitable subset of explanatory variables. To validate the developed regression models, 15 percent of the observed data were randomly selected as reserved data and prediction models developed from 85 percent of the observed data were used to predict times for the reserved data. A Chi-square test was

Table 2.2 Length (in mile) and classification of road segments along 107 routes from sawmills to energy plants in the western Oregon

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.9	129	138.9	158
2	1.9	0.7	1.4	0	1.9	0.3	0.5	0.1	22.3	4.2	2.7	0.6	18.3	2.1	2.5	0.6	13.6	42.7	116.5	168
3	0.2	0	0	0	0.7	0.1	0	0	4.1	0.1	0	0	6.2	0.1	0	0.1	9.3	152	172.6	226
4	0.7	0.3	0.1	0	4.5	0.6	0.7	0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0	22.3	8.4	104.2	143
5	0	0	0	0	0.2	0	0	0	2.6	0	0	0	0.1	0	0	0	4.9	113	120.9	132
6	0	0	0	0	1.0	0	0	0	20.3	0	0	0	8.4	0	0	0	14.8	108	152.6	208
7	0.3	0	0	0	0.8	0	0	0	12.0	0.2	0.1	0	15.4	0.1	0	0	18.9	28.3	76.1	122
8	0.7	0.3	0.1	0	4.5	0.6	0.7	0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0	12.7	0	86.2	121
9	0.4	0.1	0.1	0	3.3	1.1	0.8	0	30.3	0	1.0	0.1	20.5	3.5	1.0	0	10.8	13.9	87.1	109
10	0.5	0.2	0.1	0	4.0	0.5	0.8	0	28.0	5.7	3.7	0.1	26.3	1.9	1.5	0	11.6	2.3	87.4	118
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13.8	30.7	44.5	61
12	0.7	0.3	0.1	0	3.6	0.6	0.7	0	25.9	4.7	2.7	0.2	25.7	2.3	1.5	0	14.8	8.4	92.2	157
13	0.7	0.3	0.1	0	4.0	0.6	0.7	0	27.1	4.6	2.7	0.2	27.2	2.2	1.6	0	6.9	0	78.6	90
14	0	0	0	0	0.4	0	0	0	7.4	0	0	0	6.3	0	0	0	8.6	20.1	42.8	60
15	0	0	0	0	0.2	0	0	0	8.1	0	0	0	3.2	0	0	0	5.9	13.5	30.9	45
16	0	0	0	0	0.4	0	0	0	7.4	0	0	0	6.3	0	0	0	13.1	4.4	31.5	60
17	0.8	0.2	0	0	2.9	0	0.1	0	37.4	1.5	0.4	0	27.6	0.9	0.5	0	15.8	153.3	241.4	284
18	0.7	0.3	0.1	0	4.0	0.6	0.7	0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0	20.4	82	174.2	233
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
107	4.8	0.3	0.3	0.1	7.5	0.8	0.6	0.3	44.7	4.7	2.3	0.6	47.1	3.8	4.4	1.8	18.2	0	142.1	175

used to evaluate the differences between observed and predicted travel times. In our data analysis, both the acceptable error level (E% = 5) and the significance level were set to 5% (α = 0.05).

2.3 RESULTS AND DISCUSSION

2.3.1 Transportation times

2.3.1.1 Travel times

The transportation data provided by Terrain Tamers only included information related to loaded trips; unloaded trips were not recorded. During the study period a total of 21,945 trips were made using 107 routes. Each route was repeatedly traveled in the range from 5 to 3893 trips. A total of 64 mills or lumber companies were identified as sources of wood raw materials. These were located in western Oregon. The materials were transported to 31 energy or chip conversion facilities near the I-5 freeway or to ocean terminals on the Oregon Coast. While most of the hog fuel, shaving, and sawdust were hauled to energy plants, clean chips were transported to the ocean terminals for export to Japan or to pulp mills.

For the 107 identified routes, total one-way travel distances ranged from 8.2 to 244 miles, with the average travel distance being 98 miles. Average travel times varied from 1.39 to 1.83 minutes per mile (43.2 to 32.7 miles per hour). These times are comparable with those from past studies. Fei et al. (2008) reported that the average loaded travel speed was 44.14 miles per hour on a two-lane state highway located in Arizona. Groves et al. (1987) found slightly lower travel speeds (40.1 to 27.2 miles per hour) compared to our study. However, their study was related to the transport of sawlogs from forest landings to sawmills. Thus their average travel speed was determined by on-forest roads as well as on-highway roads.

Transportation times were strongly correlated with travel distance ($r^2 = 0.89$). As shown in Table 2.2, however, travel times for similar distances, but over different routes, varied by up to 33%. The differences between travel times could be explained by several road alignment variables such as road grade, radius of curvature, and number of curves in the travel route. Of the 107 different routes, most did not include road classes with sharp curves. Only 16 routes included all 18 road classes. About half of the total traveled distance was found in road class 18 (freeway), the average travel distance of this road class being 48.9 miles per a trip. The combination of road class 9 (straight segments with good grade), road class13 (straight segments with downhill grade), road class 17 (urban road), and road class 18 (freeway) accounted for 92 percent of the total travel distance. Therefore, the high proportions of these classes in each route would greatly affect overall travel time and these classes could be considered to be the main explanatory variables in prediction models for estimating total travel times.

2.3.1.2 Loading and unloading times

Loading and unloading times generally depend upon the loading and unloading systems, the transported materials, the size of trailers and the waiting times to load or unload. In this study, loading times started with entering the mill or lumber company's yard and ended with weight scaling of the chip van after loading the wood raw materials. Unloading times at the conversion facilities or ocean terminal included similar activities as those for loading time. Therefore, both loading and unloading times included some waiting times for loading or unloading as well as actual loading or unloading times.

Average loading and unloading times were summarized based on the type of material transported and the trailer size (Tables 2.3 and 2.4). Hog fuel has significantly shorter average loading and unloading times than other materials ($p < 0.05$). The shorter loading and unloading times could be explained by the characteristics of the material being handled (particle size, bulk density and water content). Hog fuel has bigger particle size and lower bulk density compared to the other materials. In addition, hog fuel is generally wet - substantially in excess of 50 percent by weight (Angus-Hankin et al. 1995). Compared with other materials, smaller volumes of hog fuel would need to be loaded and unloaded into the same size of trailer and, therefore, times could be expected to be shorter.

Table 2.3 Loading and unloading times by transported materials

	Hogfuel	Chips	Shavings	Sawdust	*p*-value
	Mean ± Standard deviation (minutes)				
Loading time	30.5 ± 10.8 a[*]	39.9 ± 11.6 b	40.3 ± 16.8 b	43.3 ± 10.6 b	0.036
Unloading time	32.0 ± 6.0 a	45.6 ± 15.3 b	49.5 ± 17.7 b	52.1 ± 15.0 b	0.047

[*] Materials with the same letter do not have significantly different loading times or unloading times.

Table 2.4 Loading and unloading times by size of trailers

	Single trailer	Double trailer	*p*-value
	Mean ± Standard deviation (minutes)		
Loading time	21.6 ± 3.9 a[*]	38.8 ± 16.6 b	0.054
Unloading time	31.0 ± 14.7 a	48.3 ± 4.3 b	0.047

[*] Trailer configurations with the same letter do not have significantly different loading times or unloading times.

The hauling company assigned single or double trailers to mills or lumber companies according to their specific loading systems, travel route available for each truck configuration, and volume of transported materials. In this study, there was a significant difference in loading and unloading times among the trailer sizes (Table 2.4). Single trailers had the shortest average loading and unloading time compared to double trailers (p>0.05). The primary difference in loading and unloading times between single and double trailers is due to the volume and potential load capacity of trailer. Double trailers used in this study were 9 ft longer in total trailer length and had

3000 lbs more load capacity than single trailers. However, the time differences between two trailer sizes were considerably larger than the volume differences of trailers. Time differences could also be explained by several other factors such as waiting times and systems employed to load and unload, although these factors were not surveyed in this study. In loading systems, most of the wood raw materials were conventionally loaded into enclosed trailers from the top by short conveyor, hopper or loading equipment such as a bucket loader in the saw mills or lumber companies. Loading by stationary hoppers was commonly used at larger facilities while short conveyors and bucket loaders were used in relatively small facilities. A representative from the hauling company in this study also commented that the hopper loading system was much faster and more convenient in loading than the other systems because it does not require any other additional equipment and is available for loading by the truck drivers. The effects of loading and unloading techniques on loading and unloading times have also been recognized by Angus-Hankin et al. (1995). They suggested that systems which use end dumping of trailers are very time efficient for unloading but these are usually used at larger facilities. They also suggest that self-unloading systems, such as those which incorporate a walking floor or live floor within the trailer, could be most cost effective for unloading at small facilities; they do not need additional equipment and can also reduce the waiting time to unload at the destination because they can unload transported materials within any area of the storage yard. However, self-unloading vans are more expensive and heavier than regular chip vans because of the installed additional equipment for self-unloading. In addition, these vans have lower load capacity than possum belly chip vans because walking or live floor trailers can only be operated on flat bottom trailers. Heavier weight and lower load capacity of live floor trailers may be reflected in the delivery price for routes having long travel distances.

2.3.2 Prediction models

2.3.2.1 *Travel times*

A prediction model was developed to estimate the travel times based on the road classes. It would also allow the investigation of the effects of road class on transporting of woody biomass. This information would be useful firstly, to hauling contractors deciding which routes to use for chip vans and secondly as the basis for the development of optimal truck scheduling systems that could lead to reduced transportation costs.

In this study, the distance on various road classes positively affected the travel time. Only four specific road classes (road classes 9, 13, 17 and 18) were initially selected as significant variables ($p<0.05$) to predict the travel times. However, the initial prediction model did not fit logically. For example, the model would predict exactly the same travel time for a route that included solely 50 miles of road class 18 (freeway) as it would for a route that included 25 miles of road class 10 (good grade, 700 to 1000 ft radius of curvature) as well as the 50 miles of freeway. Therefore, road classes excluded from the previous model were combined as ‘other classes’ to account for the entire road classes and then added into new prediction models. The final prediction model was developed with five road classes that have significant *p*-values ($p<0.05$) and the adjusted R-square was improved to 97% (Table 2.5). The regression coefficients suggested that given the same distance, the distance of urban roads (class 17) had the greatest effect on travel time, while the influence of distance in other road classes was somewhat less. The prediction model implied that travel times might be reduced by selecting routes having short urban road distances. A shorter travel time could also be achieved by traveling more on freeways.

Table 2.5 Prediction model to estimate travel times

Prediction models	Travel distance (miles) in each class	Variable range (miles)	Mean (miles)	r^2	n[a]	Validation *p*-value[b]
Travel times (minutes)	= 5.575			0.97	93	0.54
	+ 1.204 (Class 9[c])	0 to 48.3	16.64			
	+ 1.387 (Class 13[d])	0 to 47.1	14.75			
	+ 2.017 (Class 17[e])	1.3 to 27.6	11.31			
	+ 1.168 (Class 18[f])	0 to 233.7	48.14			
	+ 0.944 (Other classes[g])	0 to 32.1	8.08			

[a] 85 percent of the total observed data that were used in developing of prediction models.
[b] *p*-value provided by Chi-squared test between predicted and observed travel times.
[c] Road class 9: Straight road segments with good grades of road in miles.
[d] Road class 13: Straight road segments with downhill grades of road in miles.
[e] Road class 17: Urban road in miles.
[f] Road class 18: Freeway in miles.
[g] Other road classes without road class 9, 13, 17, and 18 in miles.
All variables included in the equations have significant *p*-value less than 0.05.

From the prediction model, average travel speeds (miles per hour) for different road classes was estimated (Table 2.6). Average travel speed was lowest in the urban road class (29.7 miles per hour). This value is closely comparable with the speed limit (35 miles/hr) on urban roads. However, the highest travel speeds were found in the "other road classes" which include several classes with rolling and mountainous curves with adverse road grade. It is not logical that these road classes would have the highest travel speed associated with them. This anomaly may be due to a small sample size for these road classes and high variation associated with them. Analyses showed that correlation between road classes was small. Excluding the "other road classes", freeway (class 18) travel was slightly faster than highway travel (class 9 and 13) and downhill travel (class 13) on highway with good alignment showed slower travel speed compared to the travel on good road grade (class 9).

Table 2.6 Average travel speeds (miles/hour) for different road classes

	Road classes				
	Class 9[a]	Class 13[b]	Class 17[c]	Class 18[d]	Other[e]
Average Travel Speed (miles/hr)	49.8	43.3	29.7	51.4	63.6

[a] Road class 9: Straight road segments with good grades of road.
[b] Road class 13: Straight road segments with downhill grades of road.
[c] Road class 17: Urban road.
[d] Road class 18: Freeway.
[e] Other road classes without road class 9, 13, 17, and 18.

2.3.2.2 Loading and unloading times

Loading and unloading times are affected by both transported materials and trailer size. In our regression equations both variables were assigned as dummy variables to represent the subgroup of the samples and all variables significantly ($p < 0.05$) influenced loading and unloading times (Table 2.7). From the analysis of dummy variables, we found that the loading and unloading times for double trailer units transporting hog fuel was significantly lower, by 10.62 minutes and 23.09 minutes respectively, than units transporting sawdust. Single trailer units transporting hogfuel had predicted loading and unloading times that were 24.78 and 43.93 minutes lower, respectively. The effects of trailer size were more obvious than those of transportation materials in unloading times. The time difference between single and double trailer unloading times was 20.8 minutes. The large difference may be explained by unloading systems. Single trailers are sometimes unloaded by an end dumping system but this would be more difficult for double trailers.

Our prediction models indicated that the independent variables (transported materials and trailer size) explained only 27 and 32 percent of the variation in loading and unloading times, respectively. R-square values in regression models are often used as one of the good indicators for the effectiveness of prediction equations. However, this value does not necessarily indicate the best equation to predict the dependent variable (Kozak and Kozak 2003). Therefore, validations of prediction models are often performed to ascertain their adequacy.

Table 2.7 Prediction models to estimate the loading and unloading times

Prediction models	Transported materials and trailer sizes	r^2	n[a]	Validation *p*-value[b]
Loading times (minutes)	= 44.25 – 10.62 (Hogfuel[c]) – 3.26 (Chip[d]) – 1.97 (Shaving[e]) – 14.16 (Single trailer[f])	0.27	93	<0.01
Unloading times (minutes)	= 55.11 – 23.09 (Hogfuel) – 7.86 (Chip) – 1.94 (Shaving) – 20.84 (Single trailer)	0.32	93	<0.01

[a] 85 percent of the total observed data that were used in developing of prediction models.

[b] *p*-value provided by Chi-squared test between predicted and observed travel times.

[c] Dummy variables for transported materials (Hogfuel = 1 and others = 0).

[d] Dummy variables for transported materials (Chip = 1 and others = 0).

[e] Dummy variables for transported materials (Shaving = 1 and others = 0). Therefore, saw dust was represented by hogfuel, chip, and shaving = 0.

[f] Dummy variables for trailer size (Single trailer = 1 and double trailer = 0).

2.3.3 Validation of prediction models

2.3.3.1 Travel times

The prediction model for travel times was verified by comparing actual and predicted travel times on 16 reserved routes (Figure 2.1). The model validation procedures showed that the differences between the actual and predicted travel times were insignificant (*p*>0.05, Table 2.5), that means the developed regression equation provides good predictors for the travel times. All predicted travel times were within 8 minutes except one route that had a difference of 17 minutes.

The percent differences were calculated according to:

$$Percent\ difference = \frac{Predicted - Observed}{Observed} \times 100$$

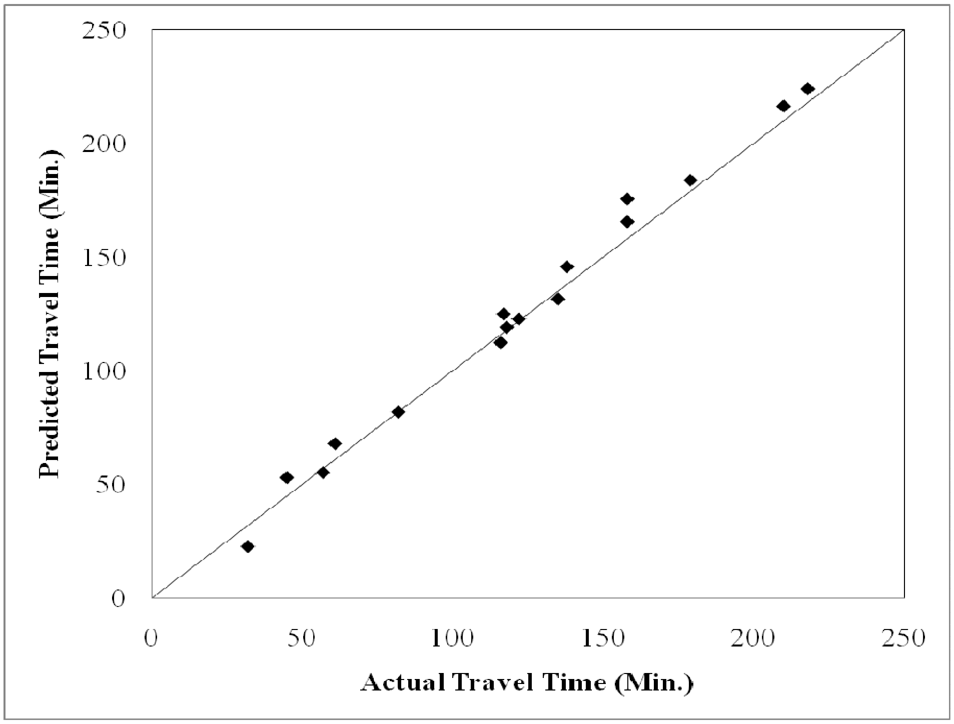

Figure 2.1 Relationship between actual and predicted travel times for chip vans

The average percent difference between actual and predicted travel times was only 6 percent. Therefore, it was concluded the prediction model was valid and could be used to accurately predict travel times for chip vans in western Oregon and southwestern Washington. However, because our model was developed based on vertical and horizontal alignments of roads, it could possibly be applied to predict travel times for chip van in other regions; assuming that other factors such as weather conditions, traffic conditions, and legal payloads were similar.

2.3.3.2 Loading and unloading times

The differences between actual and predicted loading and unloading times were calculated to verify the developed regression equations (Table 2.8 and 2.9).

Table 2.8 Predicted and actual loading times for 16 loads reserved for model validation.

Routes	Loading Times (minutes)		Difference	
	Actual	Predicted	Minutes	Percent (%)
1	29	41	12.0	41.3
2	24	32	7.8	32.3
3	22	40	18.4	83.6
4	39	34	-5.4	-13.8
5	55	34	-21.4	-38.9
6	45	41	-4.0	-8.9
7	37	39	2.1	5.7
8	40	39	-0.9	-2.2
9	30	40	10.4	34.7
10	18	19	1.5	8.2
11	27	40	13.4	49.6
12	52	42	-9.7	-18.7
13	23	19	-3.5	-15.3
14	30	42	12.3	40.9
15	37	34	-3.4	-9.1
16	25	34	8.6	34.5

Differences were significantly different for both loading and unloading times for wood raw materials ($p<0.05$). In loading time, the average time difference between actual and predicted times was 8 minutes, ranging from 0.9 to 18.4 minutes (Table 2.8). In unloading times, the difference between actual and predicted times was much larger than found for loading times. Average time and percent differences were 16 minutes and 32 percent, respectively (Table 2.9).

Table 2.9 Predicted and actual unloading times for 16 loads reserved for model validation.

Routes	Unloading Times (minutes)		Difference	
	Actual	Predicted	Minutes	Percent (%)
1	24	47	23.3	96.9
2	55	31	-23.9	-43.5
3	45	52	7.2	16.1
4	38	32	-6.0	-15.7
5	28	32	4.0	14.4
6	54	47	-6.8	-12.5
7	46	46	0.3	0.7
8	57	46	-10.7	-18.8
9	38	52	14.2	37.4
10	19	11	-7.8	-41.2
11	39	52	13.2	33.9
12	79	53	-25.8	-32.7
13	34	11	-22.8	-67.1
14	135	53	-81.8	-60.6
15	35	32	-3.0	-8.5
16	38	32	-6.0	-15.7

In model validation, the prediction models produced high errors in loading and unloading times. As noted earlier, these predictions could possibly be improved by adding other factors such as waiting times and the types of loading and unloading systems. Currently, although the differences between actual and predicted times were statistically significant, our prediction models could be potentially applied to predict loading and unloading times in the western Oregon region because our data collection was carried out for many of the conversion facilities and lumber companies in western Oregon. However, applying our prediction models in other regions should be done with caution because other regions would likely have different species, water contents and material bulk densities compared with this study.

2.4 CONCLUSIONS

High transportation costs from material sources to energy facilities have been identified as one of the economic barriers in improving the utilization of forest biomass for energy production. Therefore, a well managed transportation system could greatly reduce overall forest biomass production costs as well as transportation costs.

This study developed a road classification system and prediction models to estimate travel times and loading and unloading times for transporting wood raw materials in western Oregon and southwestern Washington. In observed travel data, travel times were strongly influenced by travel distance and average travel time per mile was 1.52 minutes. Our prediction model for estimating travel times was developed based on travel distance over various road classes and was ascertained as a good predictor for travel time through a validation procedure. The prediction model suggests that selecting the routes with shorter urban road distances and longer freeway distances would strongly reduce the travel times.

Loading and unloading times were predicted using transported materials and trailer size. Prediction models indicated that loading and unloading times of hog fuel and single trailers were significantly shorter than those of other materials and double trailers, respectively. However, the prediction models produced high, and statistically significant, errors in model validations. To improve the accuracy of the loading and unloading models, several potential factors affecting loading and unloading activities were identified.

We recognize that there are a number of limitations associated with this work. Firstly, we did not examine the effect of road alignment on travel time for forest roads since particular configurations of chip vans often limit access onto forest roads. Our study should be extended to include chip van configurations that can operate on forest roads as well as highways. Secondly, our travel data did not include unloaded trips. Although differences in travel speeds between loaded and unloaded trucks carrying forest materials may be less than 10% (Jackson 1986; B. Boyer 2010 personal communication) further work is needed on this topic. Thirdly our prediction models may not be relevant to the transport of wood raw materials in other regions which may have different material characteristics (such as species, water contents and bulk density) as well as different weather conditions and traffic conditions.

Despite these limitations this research does provide an improved understanding of the factors affecting transport times for on-highway chip vans in western Oregon and southwestern Washington. This improved understanding should lead to improved management, and potentially lower costs for transport of forest biomass materials.

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CHAPTER 3

TRUCKING PRODUCTIVITY AND COSTING MODEL FOR TRANSPORTATION OF WOODY BIOMASS

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3.1 INTRODUCTION

The use of renewable energy has been steadily considered and widely expounded as a solution to the challenges of global energy security and climate change. For instance, U. S. President Obama has commented that renewable energy could supply 10% of the nation's electricity by 2012, rising to 25% by 2025 (Obama and Biden 2009). Hydroelectricity, wind power, solar power, geothermal power, and biomass are considered as current renewable energy sources. Currently, biomass including wood and agricultural residues is the second largest source of renewable energy used to generate electricity or produce heat in U.S (Perlack et al. 2005). In particular, the use of woody biomass has great potential to produce energy in Pacific Northwest, USA due to a sustainable supply chain of energy sources. However, high production and transportation costs, compared to relatively low market values, hinder the utilization of woody biomass. Therefore, identifying or developing cost effective production and transportation systems has become an economically critical issue to expand biomass utilization.

Transportation cost in the traditional wood supply chain has been identified as the single largest component of total production costs from seedling to mill. McDonald et al. (2001) reported that transport costs accounted for about half of the delivered cost of wood raw materials in the southern USA. Ronnqvist et al (1998) suggested that small increases in efficiency of transporting from sources to conversion plants in Sweden could significantly reduce the overall production costs. Several studies have also found similar cost structures in the woody biomass supply chain. For example, Pan et al. (2008) studied the production cost of small-diameter (less than 5 inches) trees for energy. They reported the transportation cost represented 47 percent of the total cost and found them to be the largest component of the total system costs.

Transportation costs generally vary with particular travel circumstances including hauling distance, truck configurations, road conditions, transported materials, truck utilization, and road regulations. Travel distance is the dominant variable determining transportation costs. Scion (2009) identified that longer hauling distances will result in direct increases in transportation costs. Scion (2009) also noted that, as high as 60 percent of the delivered costs, can be related to transportation when hauling distances are over 100 miles. Road conditions such as vertical and horizontal alignments and surface conditions also highly influence transportation costs. Generally, forest roads have poorer road surface, more sharp curves and steeper gradients than state highways. These factors can significantly reduce travel speed of trucks and consequently increase transportation costs. Road classification systems based on road function and condition have been used to describe road segments. Groves et al. (1987) found that travel speeds were strongly related to road class ($R^2 > 95\%$) and travel routes having road classes with poor vertical and horizontal alignments have lower travel speeds and higher hauling costs. The type of material transported can also affect travel speed and transportation costs. Different types of woody biomass have different bulk densities and different moisture contents which can affect the maximum payload carried. Talbot and Suadicani (2006) reported that low bulk density and high moisture contents can decrease energy densities per load and consequently increase transportation costs. Therefore, maximizing payloads per trip through denser loads and lower moisture contents are fundamental to getting the most cost efficient transport of woody biomass materials.

Understanding of transportation cost structure through simulations of cost models can help identify possibilities for efficiency gains that may lead to increased profits or decreased costs (Casavant, 1993). In particular, a productivity and costing model would enable the user to determine and compare the costs of various hauling options, such as when transporting woody biomass from a harvesting site or mill to an energy conversion plant. A number of truck costing models have been developed both within and outside of the forest industry over the last sixty or seventy years. Mathews (1942) described one of the earliest hand-calculated truck rate models for the forest industry. Taylor (1988) described a spreadsheet-based truck costing model (TRUCKAAI) that was developed by the New Zealand Logging Industry Research Association. In Canada, the Forest Engineering Research Institute of Canada (FERIC) developed a computer model to determine the cost of transporting raw forest products from the stump to the mill in Alberta, CA (Blair 1999). The program allows the user to specify a haul fleet and haul route, and then analyze the costs of the specified haul system. Trimac Consulting Services also created a computerized activity based model for commercial grain trucking in Western Canada (Trimac Logistics Ltd., 2001). In the USA, Berwick and Dooley (1997) developed a spreadsheet simulation model to estimate truck costs for different truck configurations, trailer types, and trip movements. The effects of different variables on total trucking costs were examined in their sensitivity analysis. In the Pacific Northwest, My Fuel Treatment Planner (MyFTP) was created by the USDA Forest Service. This model mainly estimated the production and hauling costs associated with forest fuel reduction treatments but also included potential revenues from these treatments.

These past transportation cost models are limited in their applicability to different regions or countries for a number of reasons. First, travel times were often simply estimated based on payload and either one-way or round-trip distance without the consideration of road characteristics and qualities. They sometimes ignore the fact that, for the same travel distance, different road conditions and alignments may create different travel times and produce different transportation costs. Groves et al. (1987) identified that if travel times are predicted by travel distance only, in spite of different road conditions and alignments, the prediction model can produce substantial errors of up to 20% between actual and predicted times. They suggested, therefore, that a road classification system that is applicable to roads anywhere within the region of interest would be needed to improve the accuracy of truck productivity models.

In addition, most of the past cost models were developed for conventional log transportation in the forestry sector. Transporting of woody biomass is generally carried out by chip vans having solid panels (containers) to prevent the loss of small woody particles and a “possum belly” in the bottom of the trailer to increase the potential payload of trailers (Angus-Hankin et al. 1995). These specific configurations of chip vans often produce limited accessibility on forest roads and the selection of different travel routes compared to conventional log trucks. In addition, chip vans generally have relatively lighter payload per unit volume than conventional log trucks. Therefore, these specific transportation performances of chip vans may produce different cost structure compared to those of commercial log trucks.

This study was conducted to understand the cost structures in woody biomass transportation from saw-mills to conversion facilities (energy or pulp) or to export harbors in western Oregon. The primary objectives of this study were to develop a computer model to estimate the transportation productivity and cost for woody biomass and also to evaluate the effects of different truck configurations, transported material types, and travel route characteristics on transportation costs. Our developed truck costing model may provide useful information for trucking companies that need accurate truck cost information to negotiate desirable rates and determine the appropriate transportation performances. Furthermore, improved knowledge in woody biomass transportation would be helpful for increasing transportation efficiency in the trucking industry and improving the utilization of woody biomass for energy production.

3.2 STUDY METHODS

A spreadsheet based truck productivity and cost model for woody biomass transportation was developed using Microsoft Excel. The model is referred to as

BIOTRANS (Biomass Transportation model). In BIOTRANS, truck productivity and cost are determined for truck and trailer types, origin (saw-mill) and destination (plants or harbor) points in each trip, and transported woody material types that have been selected by the user.

3.2.1 Data

Data used to build BIOTRANS came from a variety of sources including interviews with a trucking company and co-operation with Oregon Department of Transportation (ODOT). Basic costing information related to chip van trucks was collected from Terrain Tamers (TT) located in Dillard, Oregon. It should be noted, however, that the costing portion of BIOTRANS was developed independently of TT and may, or may not, reflect TT's actual costs. TT also provided much of the travel time data. Travel route maps and road geometry data were provided by ODOT.

3.2.1.1 Cost information

Detailed cost information was collected through an interview with a senior transport manager from Terrain Tamers, a trucking company handling over 20,000 loads of woody biomass material per year. Transportation costs are generally divided into fixed and variable cost components. In transportation cost analysis, fixed costs are incurred whether the truck is working or not, and are assumed to be affected by output

Table 3.1 Input cost information for different truck and trailer configurations modeled in BIOTRANS.

	3 axle truck			4 axle		
	Single trailer (53')	Double trailer (32-32')	Double trailer (40-20')	Single trailer (53')	Double trailer (32-32')	Double trailer (40-20')
Purchase Price						
Truck ($)	115000	115000	115000	120000	120000	120000
Trailer ($)	70000	80000	80000	70000	80000	80000
Machine life						
Truck (miles)	750,000	750,000	750,000	750,000	750,000	750,000
Trailer (miles)	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
Salvage value						
Truck (% of purchase price)	35%	35%	35%	35%	35%	35%
Trailer (% of purchase price)	25%	25%	25%	25%	25%	25%
Interest rate (%)	8.5%	8.5%	8.5%	8.5%	8.5%	8.5%
Fuel cost ($/g)	3	3	3	3	3	3
Fuel consumption						
Fuel (mi/g)	4.4	4.4	4.4	4.4	4.4	4.4
Oil & Lube (% of fuel costs)	10%	10%	10%	10%	10%	10%
Road user charges						
Truck & Trailer ($/1000 mile)	100	100	100	100	100	100
Annual registration ($)	1200	1200	1200	1200	1200	1200
Truck & Trailer Maintenance ($/mile)	0.17	0.20	0.20	0.17	0.20	0.20
Insurance ($/mile)	0.06	0.06	0.06	0.06	0.06	0.06
Tire cost						
New truck tire cost ($/tire)	250	250	250	250	250	250
Retread truck tire cost ($/tire)	170	170	170	170	170	170
New trailer tire cost ($/tire)	350	350	1100	350	350	1100
Retread trailer tire cost ($/tire)	260	260	733	260	260	733
Tire life						
New front axle tire (mile/tire)	40000	40000	40000	40000	40000	40000
New drive axle tire (mile/tire)	50000	50000	50000	50000	50000	50000
New trailer tire (mile/tire)	45000	45000	45000	45000	45000	45000
Retread drive tire (mile/tire)	40000	40000	40000	40000	40000	40000
Retread trailer tire (mile/tire)	36000	36000	36000	36000	36000	36000
Number of front axle tires	2	2	2	2	2	2
Number of drive axle tires	8	8	8	10	10	10
Number of trailer tires	16	20	8	16	20	8
Percentage new drive tires	20%	20%	20%	20%	20%	20%
Percentage new trailer tires	20%	20%	20%	20%	20%	20%
Distance on retread compared to new tire	80%	80%	80%	80%	80%	80%

($/ton-mile) to a very small degree or not at all (Berwick and Dooley 1997). Variable costs, on the other hand, are determined by the quantity and quality of transport being undertaken. So, variable costs can have a large effect on overall transportation costs. In our model development, fixed costs were depreciation, interest, insurance, taxes, overhead, and registration fees. Variable costs included maintenance and repair, fuel, oil and lubricants, labor, and tires. These costs were varied with truck and trailer configurations. The input data used in the calculation of transportation cost is shown in Table 3.1.

3.2.1.2 Travel information

Travel information was collected from May 2007 to May 2008 in western Oregon. Travel data included pick-up and drop-off places, travel time, loading and unloading times, transported materials and truck type for each trip. From these data, we identified 45 saw-mills or lumber companies as origin places (pick-up) and 20 facilities (energy or pulp plants) or harbors as destination places (drop-off) for this model. The company used two different types of truck (3 and 4 axle trucks) and three different types of trailer (53’ single, 32-32’ double and 40-20’ double trailers) during the study period. A total of six different truck-trailer combinations were identified for this model. Transported materials were hog fuel, sawdust, shavings, and chips.

Travel routes between origin and destination points were defined by Oregon Transportation Route Map #7 provided by ODOT. Map #7 specifies allowable lengths, weights, and heights of truck for each road in Oregon. Based on this route map and travel information provided by TT, 107 loaded travel routes and 388 potential empty travel routes between origin and destination points were found for inclusion in BIOTRANS.

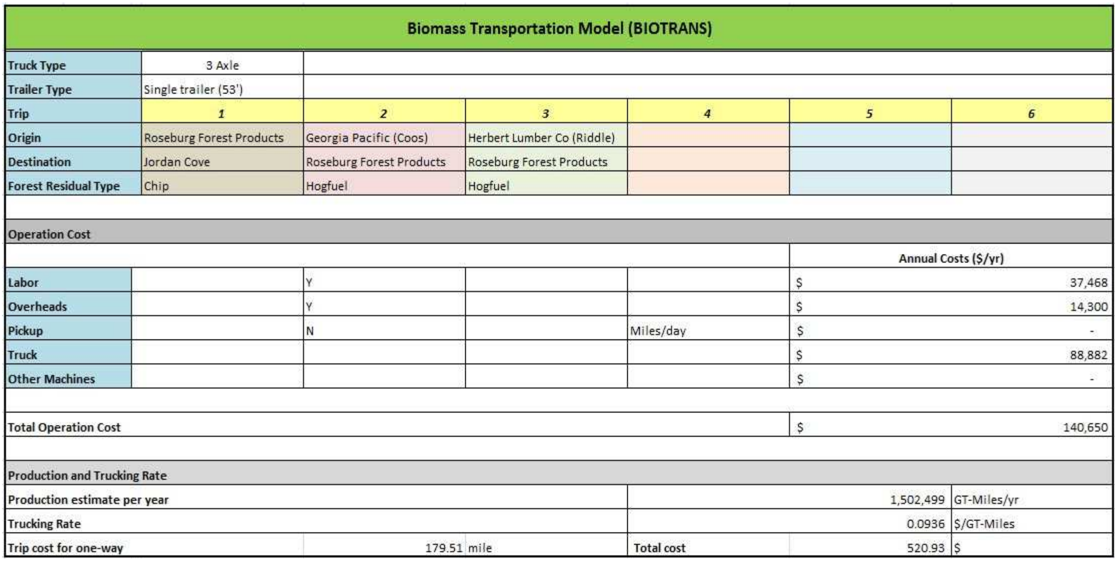
For all of the travel routes, road geometry data including horizontal and vertical curves information were obtained from ODOT. Road segments for each route were classified using the road classification systems described in Chapter 2. The total distance traveled over each road class was determined for each route. These travel distance data were then stored as raw data for each route.

For each route, a travel time was then estimated by the travel time prediction model for woody biomass transportation described in Chapter 2. In the prediction model, the estimation of travel time was determined by the travel distance of each road class on a particular travel route. However, the prediction model was limited to estimating loaded travel time because the model was developed based only on loaded trip data. Generally, empty travel time is shorter than loaded travel time due to the increase of travel resistance caused by the additional load weight. Groves et al. (1987) identified that empty travel times were about 15 percent shorter than loaded travel times for log trucks in Australia. Jackson (1986) reported that on-forest log truck travel speeds were about 4% lower for loaded travel than for unloaded travel in Oregon. Additionally, TT’s manager mentioned that unloaded travel times were 7 percent shorter on gentle road conditions or interstate highways and 12 percent shorter on poor road conditions compared to loaded travel times. Therefore, empty travel time in this study was assumed to be 90 percent of loaded travel time. Loading and unloading times were also estimated from the prediction models described in Chapter 2. Loading and unloading time estimates were based on the type of material transported and the trailer types.

3.2.2 Model description

BIOTRANS allows the user to specify a truck configuration, a haul route, the number of loads, and the type of material transported, and then analyzes the production and costs of the specified transportation system. The model was constructed with seven different linked worksheets. All of the worksheets allow the user to input their own data and cost information.

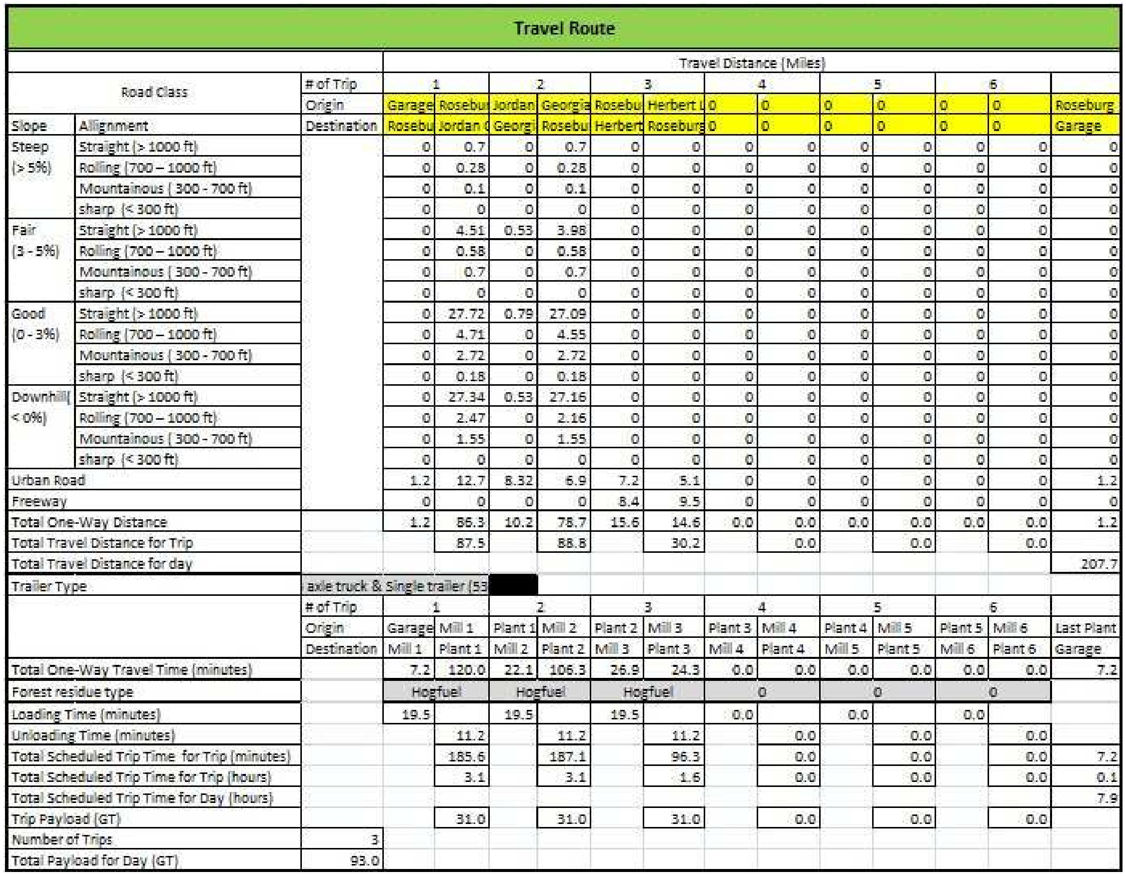
The first worksheet is a summary page that consists of two parts; the user selection part for describing route and truck data and the output part (truck production and costs) (Figure 3.1). Total trucking production and costs for a particular transport situation are determined by selecting a truck and trailer configuration, an origin, a destination, and transported material type for each trip for the day of interest. The truck type combo box allows the user to select the configuration of the truck; either 3 or 4 axles. The trailer type combo box provides a choice from three different trailer types; single (53’), double (32-32’), or double (40-20’) trailers. After selecting a truck and trailer configuration, the user can select the origin, destination, and transported material types for each trip from their combo boxes. In this model, 45 saw-mills and 20 conversion plants or harbors are used as default origins and destinations, respectively. Some combinations between origins and destinations are not appropriate because all origins are not connected with all destinations. In practice, woody biomass material from each saw-mill is transported to only 4 or 5 different destinations. Therefore, if the user chooses an inappropriate combination of origin and destination, trucking production and cost are not calculated and an error message is given. In the output part of the model, total operation cost ($/yr) is calculated by the sum of labor, overhead, and truck costs. Trucking production and cost are expressed as green ton (GT) miles per year (GT-mile/yr) and cost per GT-mile ($/GT-mile), respectively. In addition, total transportation cost for a particular working day is calculated as the total operation cost divided by total working days (270 days) per year.



Biomass Transportation Model (BIOTRANS)

Truck Type	3 Axle					
Trailer Type	Single trailer (53')					
Trip	*1*	*2*	*3*	*4*	*5*	*6*
Origin	Roseburg Forest Products	Georgia Pacific (Coos)	Herbert Lumber Co (Riddle)			
Destination	Jordan Cove	Roseburg Forest Products	Roseburg Forest Products			
Forest Residual Type	Chip	Hogfuel	Hogfuel			
Operation Cost						
					Annual Costs ($/yr)	
Labor		Y			$	37,468
Overheads		Y			$	14,300
Pickup		N		Miles/day	$	-
Truck					$	88,882
Other Machines					$	-
Total Operation Cost					$	140,650
Production and Trucking Rate						
Production estimate per year					1,502,499	GT-Miles/yr
Trucking Rate					0.0936	$/GT-Miles
Trip cost for one-way		179.51	mile	**Total cost**	520.93	$

Figure 3.1 Summary page of BIOTRANS

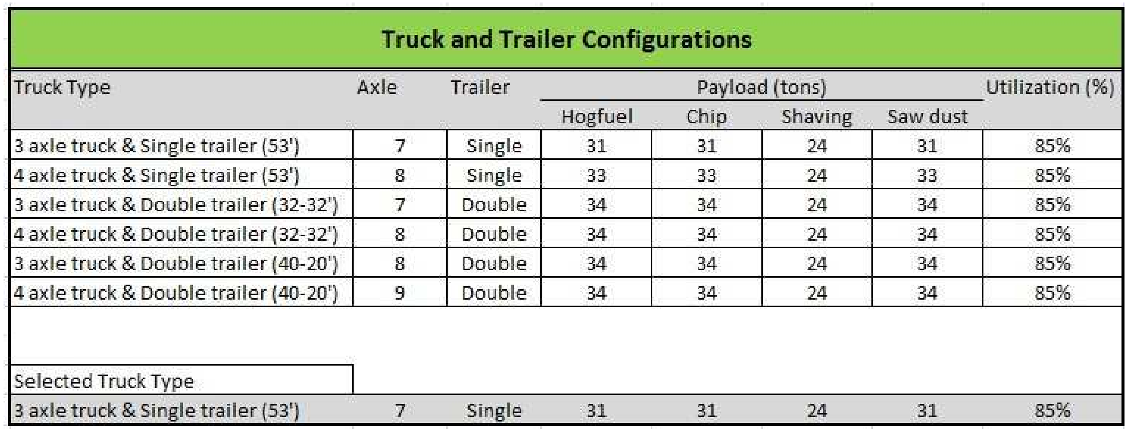


Travel Route

			Travel Distance (Miles)												
Road Class		# of Trip	1		2		3		4		5		6		
		Origin	Garage	Rosebu	Jordan	Georgia	Rosebu	Herbert L	0	0	0	0	0	0	Roseburg
Slope	Allignment	Destination	Rosebu	Jordan (	Georgi	Rosebu	Herbert	Roseburg	0	0	0	0	0	0	Garage
Steep (> 5%)	Straight (> 1000 ft)		0	0.7	0	0.7	0	0	0	0	0	0	0	0	0
	Rolling (700 – 1000 ft)		0	0.28	0	0.28	0	0	0	0	0	0	0	0	0
	Mountainous (300 - 700 ft)		0	0.1	0	0.1	0	0	0	0	0	0	0	0	0
	sharp (< 300 ft)		0	0	0	0	0	0	0	0	0	0	0	0	0
Fair (3 - 5%)	Straight (> 1000 ft)		0	4.51	0.53	3.98	0	0	0	0	0	0	0	0	0
	Rolling (700 – 1000 ft)		0	0.58	0	0.58	0	0	0	0	0	0	0	0	0
	Mountainous (300 - 700 ft)		0	0.7	0	0.7	0	0	0	0	0	0	0	0	0
	sharp (< 300 ft)		0	0	0	0	0	0	0	0	0	0	0	0	0
Good (0 - 3%)	Straight (> 1000 ft)		0	27.72	0.79	27.09	0	0	0	0	0	0	0	0	0
	Rolling (700 – 1000 ft)		0	4.71	0	4.55	0	0	0	0	0	0	0	0	0
	Mountainous (300 - 700 ft)		0	2.72	0	2.72	0	0	0	0	0	0	0	0	0
	sharp (< 300 ft)		0	0.18	0	0.18	0	0	0	0	0	0	0	0	0
Downhill(< 0%)	Straight (> 1000 ft)		0	27.34	0.53	27.16	0	0	0	0	0	0	0	0	0
	Rolling (700 – 1000 ft)		0	2.47	0	2.16	0	0	0	0	0	0	0	0	0
	Mountainous (300 - 700 ft)		0	1.55	0	1.55	0	0	0	0	0	0	0	0	0
	sharp (< 300 ft)		0	0	0	0	0	0	0	0	0	0	0	0	0
Urban Road			1.2	12.7	8.32	6.9	7.2	5.1	0	0	0	0	0	0	1.2
Freeway			0	0	0	0	8.4	9.5	0	0	0	0	0	0	0
Total One-Way Distance			1.2	86.3	10.2	78.7	15.6	14.6	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Total Travel Distance for Trip				87.5		88.8		30.2		0.0		0.0		0.0	
Total Travel Distance for day															207.7
Trailer Type		axle truck & Single trailer (53		[redacted]											
		# of Trip	1		2		3		4		5		6		
		Origin	Garage	Mill 1	Plant 1	Mill 2	Plant 2	Mill 3	Plant 3	Mill 4	Plant 4	Mill 5	Plant 5	Mill 6	Last Plant
		Destination	Mill 1	Plant 1	Mill 2	Plant 2	Mill 3	Plant 3	Mill 4	Plant 4	Mill 5	Plant 5	Mill 6	Plant 6	Garage
Total One-Way Travel Time (minutes)			7.2	120.0	22.1	106.3	26.9	24.3	0.0	0.0	0.0	0.0	0.0	0.0	7.2
Forest residue type			Hogfuel		Hogfuel		Hogfuel		0		0		0		
Loading Time (minutes)			19.5		19.5		19.5		0.0		0.0		0.0		
Unloading Time (minutes)				11.2		11.2		11.2		0.0		0.0		0.0	
Total Scheduled Trip Time for Trip (minutes)				185.6		187.1		96.3		0.0		0.0		0.0	7.2
Total Scheduled Trip Time for Trip (hours)				3.1		3.1		1.6		0.0		0.0		0.0	0.1
Total Scheduled Trip Time for Day (hours)															7.9
Trip Payload (GT)				31.0		31.0		31.0		0.0		0.0		0.0	
Number of Trips		3													
Total Payload for Day (GT)		93.0													

Figure 3.2 Travel route page of BIOTRANS

The second worksheet is the travel route information page which is linked with the summary page (Figure 3.2). This page includes route characteristics, estimated travel time, estimated loading and unloading times, and the payload for each trip. By the user selecting the origin and destination places on the summary worksheet, travel route information that is classified by 18 different road classes is automatically updated from raw source data. This information is used to estimate empty and loaded travel times using the travel time prediction model. As noted above, empty travel time in this study is assumed to be 90 percent of the estimated loaded travel time for the same trip. Loading and unloading times are estimated by prediction models based on transported materials and the truck configuration selected in the summary worksheet.

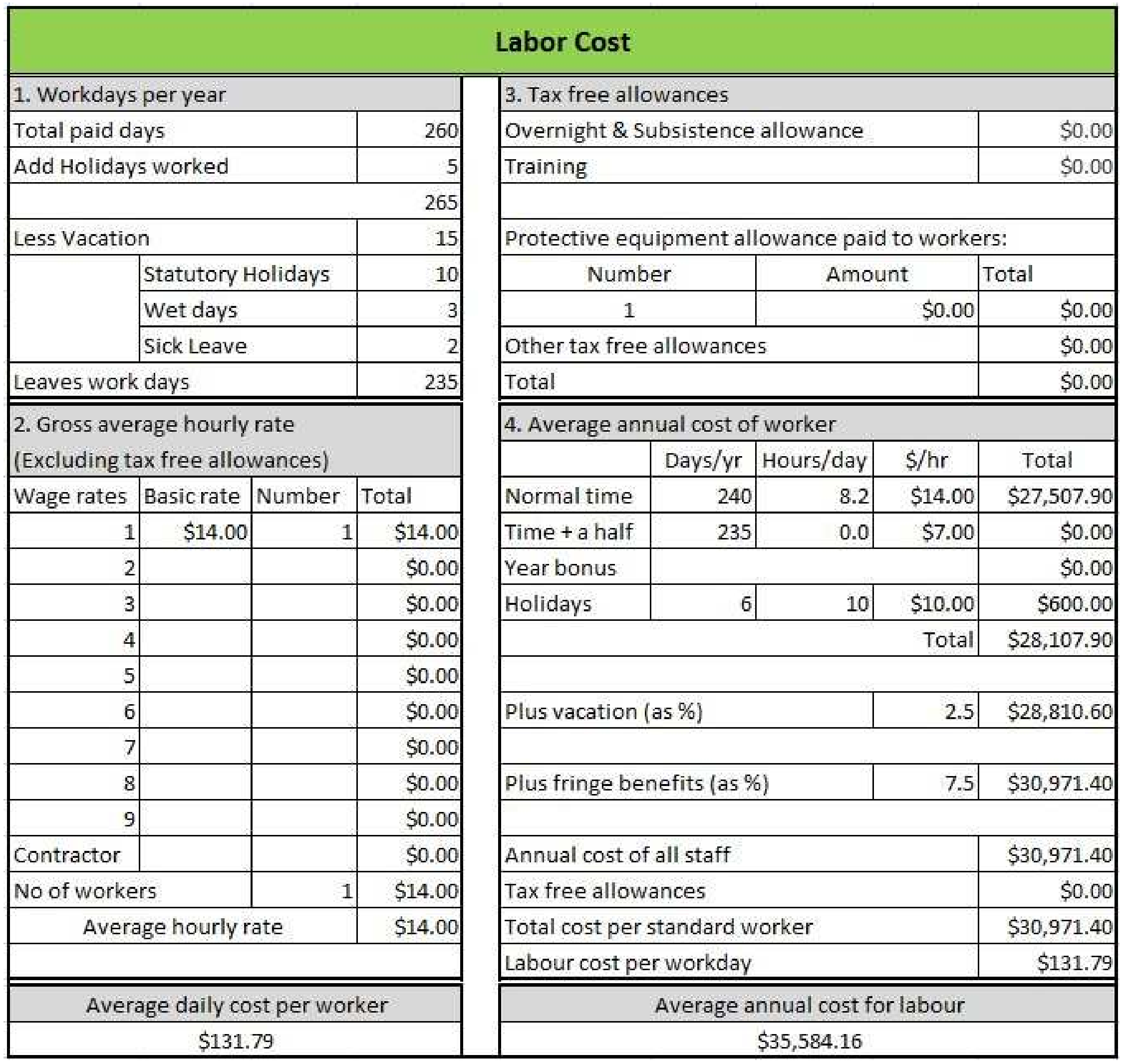


Truck and Trailer Configurations

Truck Type	Axle	Trailer	Payload (tons)				Utilization (%)
			Hogfuel	Chip	Shaving	Saw dust	
3 axle truck & Single trailer (53')	7	Single	31	31	24	31	85%
4 axle truck & Single trailer (53')	8	Single	33	33	24	33	85%
3 axle truck & Double trailer (32-32')	7	Double	34	34	24	34	85%
4 axle truck & Double trailer (32-32')	8	Double	34	34	24	34	85%
3 axle truck & Double trailer (40-20')	8	Double	34	34	24	34	85%
4 axle truck & Double trailer (40-20')	9	Double	34	34	24	34	85%
Selected Truck Type							
3 axle truck & Single trailer (53')	7	Single	31	31	24	31	85%

Figure 3.3 Truck and trailer configuration page of BIOTRANS

The third worksheet shows the truck and trailer configurations (Figure 3.3). This page is also linked with the summary worksheet. A total of six different truck and trailer combinations are used in BIOTRANS. The maximum payload for each truck and trailer type is dependent on the truck and trailer configuration and the transported material types. For a single trailer configuration, 4 axle trucks can carry 2 GT more than 3 axle trucks. However, there is no difference between 3 and 4 axle trucks for double trailer configurations. Double trailers with a 3 axle truck can carry about 10 percent more woody material than single trailers. The default time utilization for each truck and trailer was assumed to be 85 percent; in other words for each 8.5 minutes that trucks were estimated to be spending in loading, unloading and travel activities, an additional 1.5 minutes were estimated to be spent on such as activities as fueling, maintenance, safety discussion, etc.



Labor Cost

1. Workdays per year		
Total paid days		260
Add Holidays worked		5
		265
Less Vacation		15
	Statutory Holidays	10
	Wet days	3
	Sick Leave	2
Leaves work days		235

2. Gross average hourly rate (Excluding tax free allowances)

Wage rates	Basic rate	Number	Total
1	$14.00	1	$14.00
2			$0.00
3			$0.00
4			$0.00
5			$0.00
6			$0.00
7			$0.00
8			$0.00
9			$0.00
Contractor			$0.00
No of workers		1	$14.00
Average hourly rate			$14.00

Average daily cost per worker
$131.79

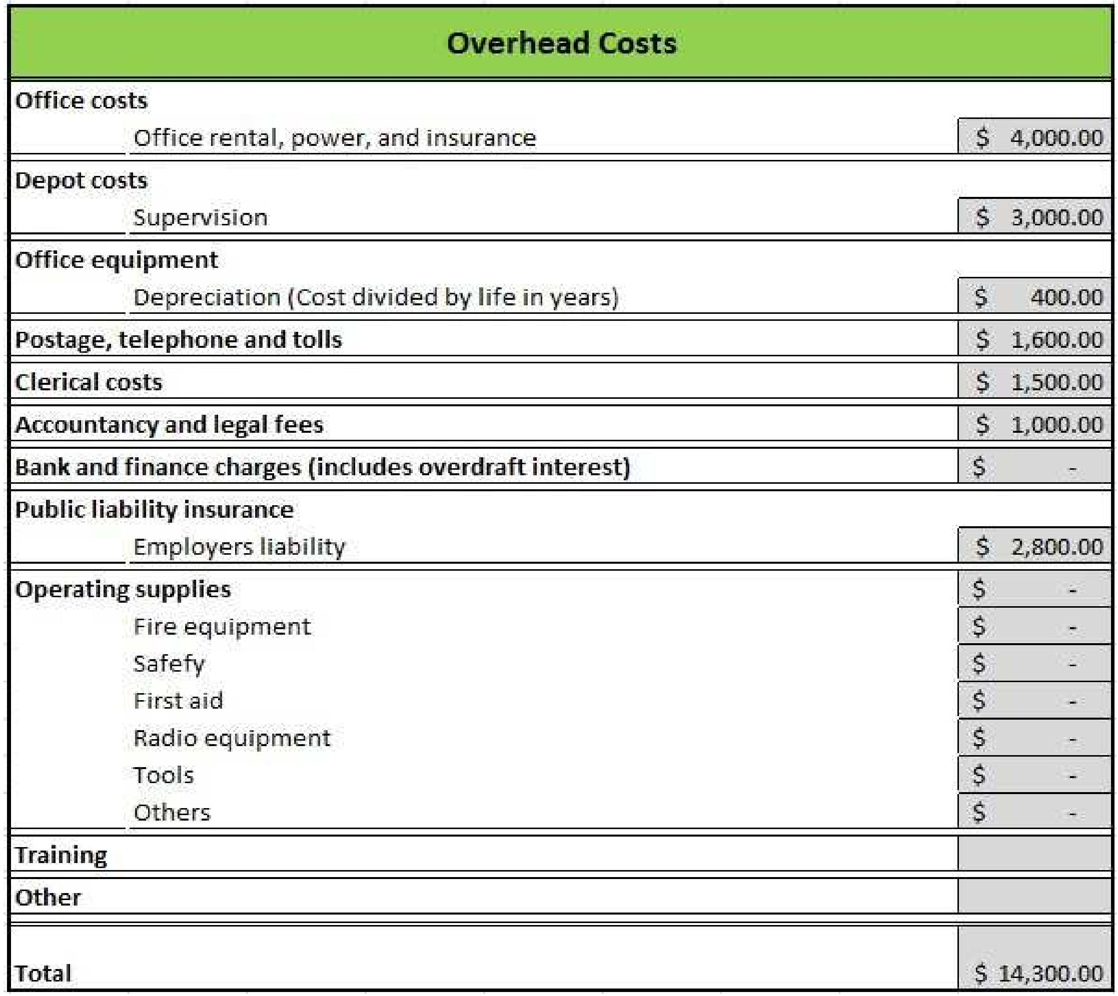
3. Tax free allowances		
Overnight & Subsistence allowance		$0.00
Training		$0.00
Protective equipment allowance paid to workers:		
Number	Amount	Total
1	$0.00	$0.00
Other tax free allowances		$0.00
Total		$0.00

4. Average annual cost of worker				
	Days/yr	Hours/day	$/hr	Total
Normal time	240	8.2	$14.00	$27,507.90
Time + a half	235	0.0	$7.00	$0.00
Year bonus				$0.00
Holidays	6	10	$10.00	$600.00
			Total	$28,107.90
Plus vacation (as %)			2.5	$28,810.60
Plus fringe benefits (as %)			7.5	$30,971.40
Annual cost of all staff				$30,971.40
Tax free allowances				$0.00
Total cost per standard worker				$30,971.40
Labour cost per workday				$131.79

Average annual cost for labour
$35,584.16

Figure 3.4 Labor cost page of BIOTRANS

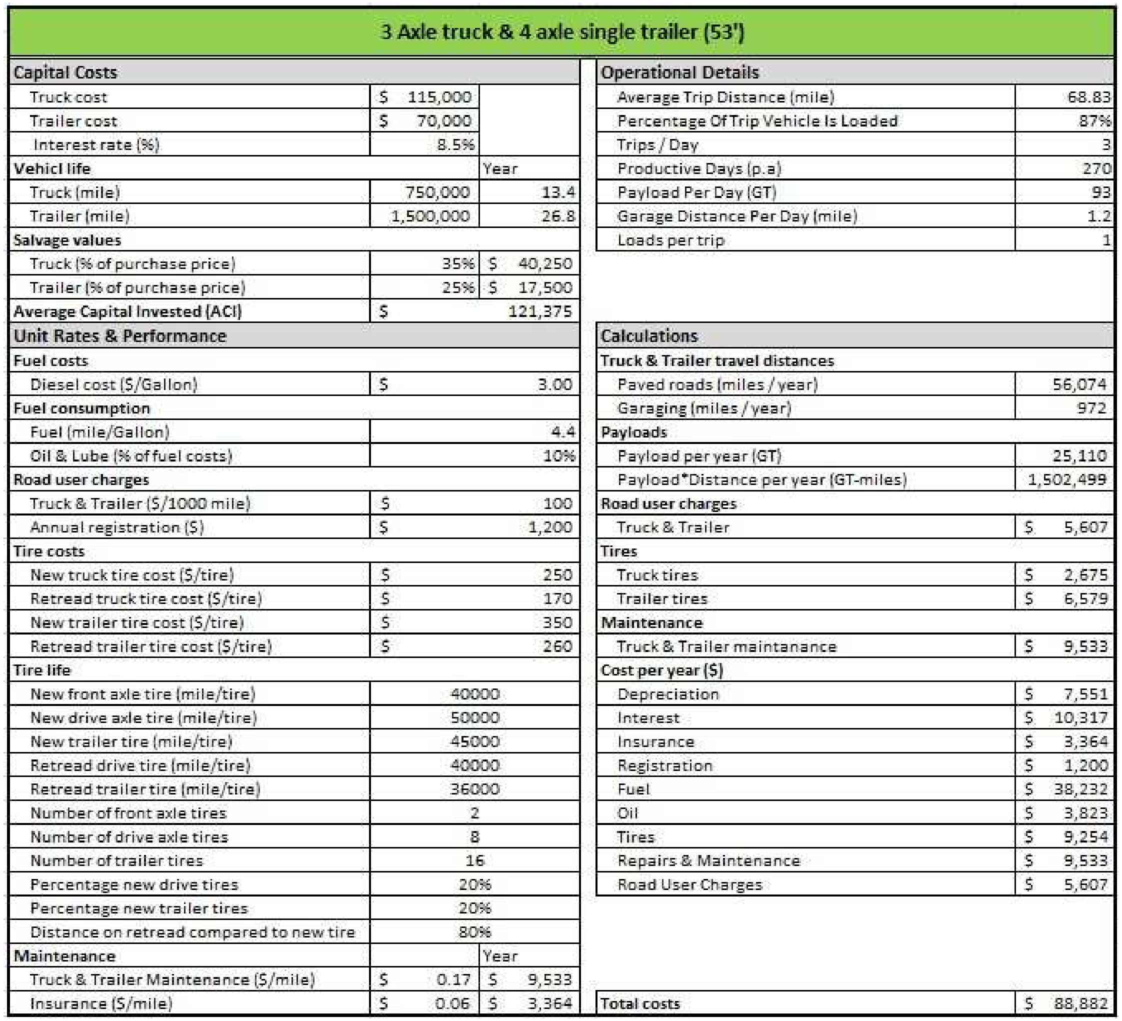
The fourth worksheet contains labor cost information (Figure 3.4). The information related to labor cost was collected from an interview with a trucking supervisor. Basic wage for a truck driver is $14 per working hour and the maximum working hours are set at 10 hours in one day (this is low for some trucking operations but the users can set higher working hours if this is more appropriate for their drivers). Payable vacation and fringe benefits are assumed to be 2.5 and 7.5 percent of average annual labor cost, respectively. Labor costs in this worksheet are calculated on a daily and an annual basis.



Overhead Costs		
Office costs		
	Office rental, power, and insurance	$ 4,000.00
Depot costs		
	Supervision	$ 3,000.00
Office equipment		
	Depreciation (Cost divided by life in years)	$ 400.00
Postage, telephone and tolls		$ 1,600.00
Clerical costs		$ 1,500.00
Accountancy and legal fees		$ 1,000.00
Bank and finance charges (includes overdraft interest)		$ -
Public liability insurance		
	Employers liability	$ 2,800.00
Operating supplies		$ -
	Fire equipment	$ -
	Safefy	$ -
	First aid	$ -
	Radio equipment	$ -
	Tools	$ -
	Others	$ -
Training		
Other		
Total		$ 14,300.00

Figure 3.5 Overhead cost page of BIOTRANS

The fifth worksheet shows overhead cost information (Figure 3.5). Overhead costs in this model include office rental, supervision, clerical, office equipments, postage and phone, and public liability costs. This type of information is likely to be recorded for the total fleet of trucks. Therefore, an average overhead cost for each truck needs to be calculated, possibly by dividing total overhead costs by the total number of trucks in the fleet.



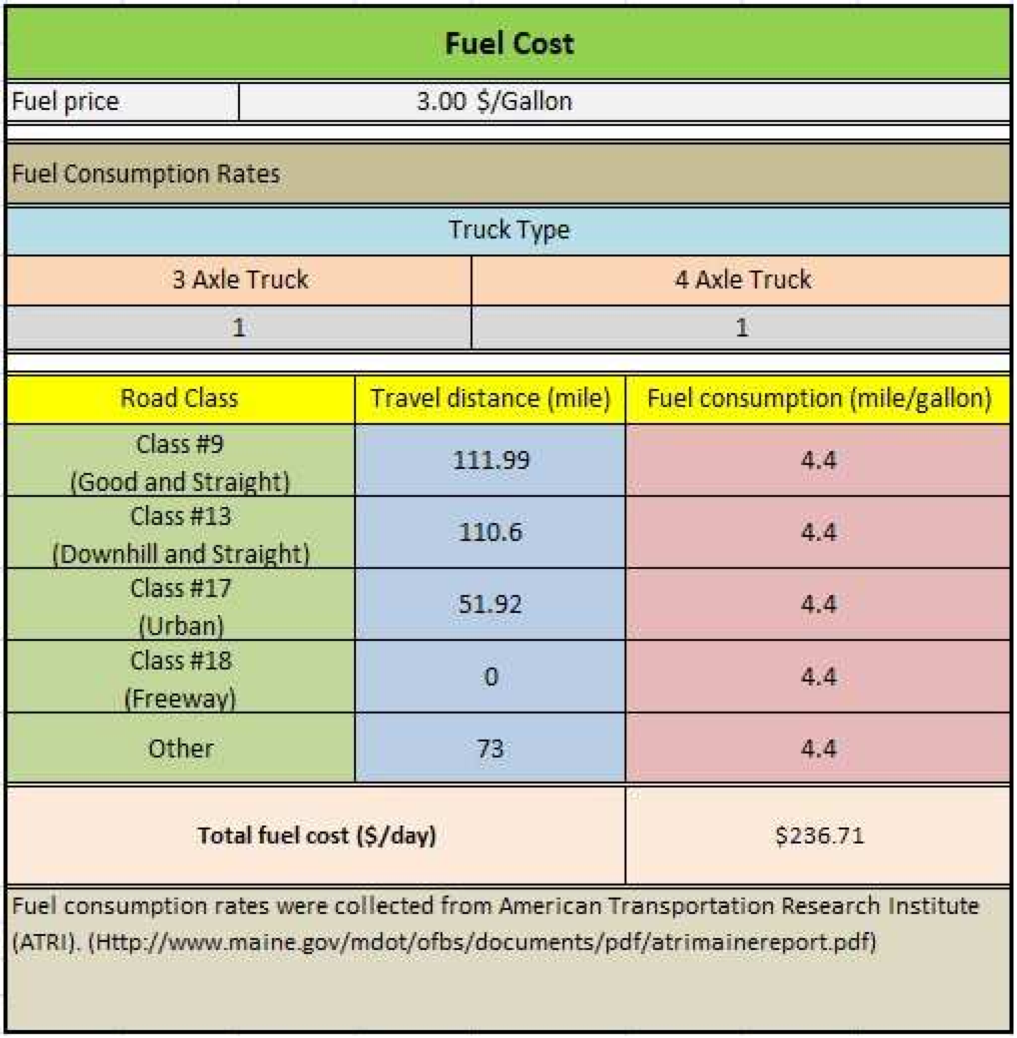
3 Axle truck & 4 axle single trailer (53')

Capital Costs		
Truck cost	$ 115,000	
Trailer cost	$ 70,000	
Interest rate (%)	8.5%	
Vehicl life		Year
Truck (mile)	750,000	13.4
Trailer (mile)	1,500,000	26.8
Salvage values		
Truck (% of purchase price)	35%	$ 40,250
Trailer (% of purchase price)	25%	$ 17,500
Average Capital Invested (ACI)	$	121,375
Unit Rates & Performance		
Fuel costs		
Diesel cost ($/Gallon)	$	3.00
Fuel consumption		
Fuel (mile/Gallon)		4.4
Oil & Lube (% of fuel costs)		10%
Road user charges		
Truck & Trailer ($/1000 mile)	$	100
Annual registration ($)	$	1,200
Tire costs		
New truck tire cost ($/tire)	$	250
Retread truck tire cost ($/tire)	$	170
New trailer tire cost ($/tire)	$	350
Retread trailer tire cost ($/tire)	$	260
Tire life		
New front axle tire (mile/tire)	40000	
New drive axle tire (mile/tire)	50000	
New trailer tire (mile/tire)	45000	
Retread drive tire (mile/tire)	40000	
Retread trailer tire (mile/tire)	36000	
Number of front axle tires	2	
Number of drive axle tires	8	
Number of trailer tires	16	
Percentage new drive tires	20%	
Percentage new trailer tires	20%	
Distance on retread compared to new tire	80%	
Maintenance		Year
Truck & Trailer Maintenance ($/mile)	$ 0.17	$ 9,533
Insurance ($/mile)	$ 0.06	$ 3,364

Operational Details	
Average Trip Distance (mile)	68.83
Percentage Of Trip Vehicle Is Loaded	87%
Trips / Day	3
Productive Days (p.a)	270
Payload Per Day (GT)	93
Garage Distance Per Day (mile)	1.2
Loads per trip	1
Calculations	
Truck & Trailer travel distances	
Paved roads (miles / year)	56,074
Garaging (miles / year)	972
Payloads	
Payload per year (GT)	25,110
Payload*Distance per year (GT-miles)	1,502,499
Road user charges	
Truck & Trailer	$ 5,607
Tires	
Truck tires	$ 2,675
Trailer tires	$ 6,579
Maintenance	
Truck & Trailer maintanance	$ 9,533
Cost per year ($)	
Depreciation	$ 7,551
Interest	$ 10,317
Insurance	$ 3,364
Registration	$ 1,200
Fuel	$ 38,232
Oil	$ 3,823
Tires	$ 9,254
Repairs & Maintenance	$ 9,533
Road User Charges	$ 5,607
Total costs	$ 88,882

Figure 3.6 Truck and trailer cost page of BIOTRANS

The sixth worksheet shows the fixed and variable cost information for each truck and trailer configuration (Figure 3.6). Default input values used in this page are presented in Table 3.1.



Fuel Cost

Fuel price	3.00 $/Gallon

Fuel Consumption Rates

Truck Type

3 Axle Truck	4 Axle Truck
1	1

Road Class	Travel distance (mile)	Fuel consumption (mile/gallon)
Class #9 (Good and Straight)	111.99	4.4
Class #13 (Downhill and Straight)	110.6	4.4
Class #17 (Urban)	51.92	4.4
Class #18 (Freeway)	0	4.4
Other	73	4.4
Total fuel cost ($/day)		$236.71

Fuel consumption rates were collected from American Transportation Research Institute (ATRI). (Http://www.maine.gov/mdot/ofbs/documents/pdf/atrimainereport.pdf)

Figure 3.7 Fuel cost page of BIOTRANS

The seventh worksheet shows the fuel cost and consumption information for different truck configurations and road classes (Figure 3.7). In BIOTRANS, we initially used a fixed fuel consumption rate of 4.4 miles per gallon even though there may be different consumption rates for different truck configurations and road classes. However, BIOTRANS users are allowed to input different fuel consumption rates that suit the particulars of their trucking operations.

3.2.2.1 Fixed costs

Purchase prices for 3 axle and 4 axle trucks were $115,000 and $120,000, respectively. Trailer price can vary depending on configuration. The purchase price of a double trailer is $10,000 higher than that of a single trailer.

Depreciation for truck and trailers was determined on a straight-line basis. Depreciation was calculated by subtracting the salvage value from the purchase price and dividing this figure by the estimated machine life. The estimation of machine life is difficult because machine life primarily depends on the mileage and condition of the machine. In this model, the machine life for the truck and trailer is determined by the annual mileage used. In the calculation of machine life, a maximum useful mileage is set at 750,000 miles for trucks and 1,500,000 miles for trailers. The default salvage value used is 35 percent of purchase price for truck and 25 percent of purchase price for trailer.

Interest is the cost of using funds over a period of time. For example, if investment funds are borrowed from banks or other funding sources, the interest rate is generally decided by the lender. Interest rates may vary with locality and lending institution. In this study, the default value for interest is 8.5 percent of the average capital invested (ACI). ACI was calculated as following:

$$ACI = \frac{Purchase\ price - Salvage\ value}{2} + Salvage\ value$$

Every equipment owner may have one or more insurance policies for protection against damage, fire, and other destructive events. Insurance costs are different depending on equipment, travel regions, and equipment utilization. In the literature, insurance costs are generally calculated from ACI. In this study, however, a default insurance fee was set at $0.06 per mile.

Other fixed costs associated with a truck and trailer are registration cost and road user charges. The annual registration cost was set at $1,200 per truck and trailer and road user charges were applied as $100 per every 1000 mile.

3.2.2.2 Variable costs

In BIOTRANS, the maintenance and repair costs were dependent on the truck and trailer configuration selected. While trucks with single trailers were set at $0.17 per mile, trucks with double trailers were set at $0.20 per mile.

Fuel costs were determined by gas price ($/gallon) and fuel consumption (miles/gallon) of the equipment. Fuel consumption depends on such factors as engine capacity (horse-power), equipment weight, travel speeds, and driver habits. It also varies between loaded and unloaded travel. In BIOTRANS, fuel consumption was initially fixed in the fuel cost worksheet at 4.4 miles per gallon regardless of truck and trailer configurations, travel speeds, and travel characteristics. The effects of different fuel consumption rates in different road classes are shown in the following section on sensitivity analysis. The default gas price was $3.00 per gallon. Oil and lubricant costs was calculated as 10 percent of total fuel costs.

Tire costs are generally determined by truck and trailer configurations, loaded weight, and mileage used. Initial purchase prices can differ for truck tires and trailer tires. In addition, tire prices can also vary with the tire quality (new vs. retreaded) and the size (regular vs. wide). In BIOTRANS, retreaded tires were assumed to be used 80% of the time for the drive axle of the truck and all axles of the trailers. The usage of new tires on these axles was set at 20 percent. Wide tires were assumed to be used only for one of the double trailer (40-20’) configurations. Tire costs for a truck and trailer were calculated as following:

$$Tire\ cost\ = Tire\ cost\ for\ truck\ +\ Tire\ cost\ for\ trailer$$

$$Tire\ cost\ for\ truck = TD * \left[\frac{NF}{LF} * CNT + \frac{ND}{LND} * CNT * 20\% + \frac{ND}{LRD} * CRT * 80\%\right]$$

$$Tire\ cost\ for\ trailer\ = TD * \left[\frac{NT}{LNT} * CNR * 20\% + \frac{NT}{LRT} * CRR * 80\% \right]$$

Where

TD: Travel distance

NF: Number of front axle tires

ND: Number of drive axle tires

NT: Number of trailer tires

LF: Useful life of front axle tire

LND: Useful life of new drive axle tire

LRD: Useful life of retreaded drive axle tire

LNT: Useful life of new trailer tire

LRT: Useful life of retreaded trailer tire

CNT: New truck tire cost

CRT: Retreaded truck tire cost

CNR: New trailer tire cost

CRR: Retreaded trailer tire cost

BIOTRANS was developed based on data from western Oregon and southwestern Washington. Therefore, origin and destination places and travel route data will not apply to other regions. For this reason, the model format was kept uncomplicated to allow its users to provide their own travel and cost information. If users can add or update travel route data for their regions following the road classification system used in BIOTRANS, it may be applicable for estimating trucking productivity and costs for their trucking situations. In addition, the user can change our basic cost information in the worksheets to their machine and cost information. BIOTRANS can be used to plan and optimize woody biomass transportation by allowing the user to vary truck configurations, travel routes and other transportation cost parameters.

3.2.3 Sensitivity analysis

Sensitivity analyses are often used to test the effects of decision variables on performance measures; in this case productivity or transportation costs. For this study, a base case scenario was developed around which sensitivity analysis was carried out. In the base case scenario, the truck and trailer configuration was a 3 axle truck with single trailer (53’). The transported woody material was hog fuel and the truck payload was 31 GT per load. A typical daily trip consisted of three loads and the total travel distance was assumed to be 207 miles. Loaded travel was 87 percent of total travel distance; a very efficient trip schedule. Additional input information included labor at $14 per hour, fuel price at $3.00 per gallon, an interest rate of 11 percent, maintenance and repair costs of 17 cents per mile, and tire costs of 16 cents per mile.

After the base case analysis was completed, sensitivity analyses were performed to test the effects of travel distance and fuel price on transportation costs for hauling woody biomass. Different one-way distances were simulated to test the effect of hauling distance on transportation cost. The fuel price influence on the transportation cost was determined by assuming different diesel prices. Additional sensitivity analyses were also conducted to test the influence of a 10% change in labor or maintenance and repair costs on transportation cost. By carrying out sensitivity analyses, the user can obtain an improved understanding of the variables which have the greatest impacts on transportation cost and may help the user to determine optimal operating options for minimizing costs.

3.3 RESULTS AND DISCUSSION

3.3.1 Truck operating cost components

Truck operating cost components vary with different transportation circumstances including truck configurations, road conditions, travel routes, regions, and fuel prices. Figure 3.8 provides the distribution of component costs, based on the average transportation circumstances in western Oregon as reported by Terrain Tamers and as modeled in BIOTRANS.

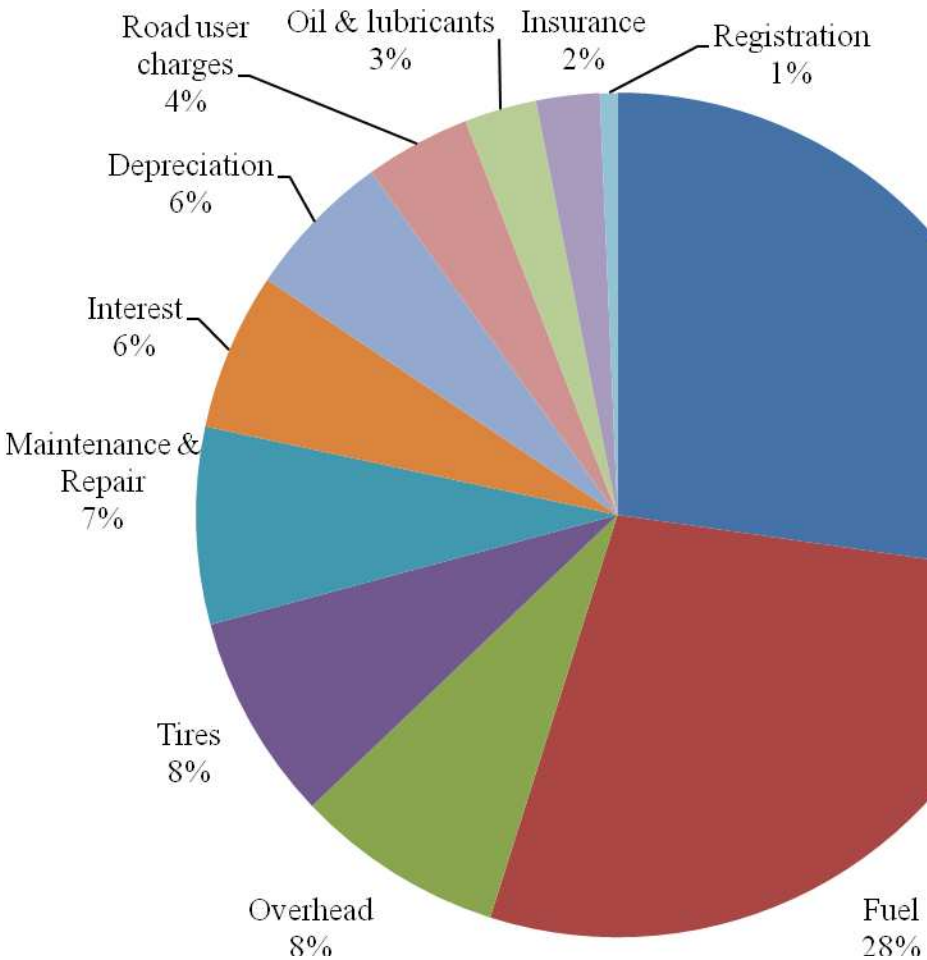


Figure 3.8 Truck operating cost components

Labor (27%) and fuel (28%) costs are the two largest components of total cost. Therefore, small reductions in labor and fuel components could significantly reduce the overall truck operating costs. Labor costs are generally calculated based on working hours per day. Therefore, optimal truck dispatching systems could be considered to reduce the working hours. Optimal truck dispatching may reduce the empty travel time and delay time for loading and unloading activities. Fuel costs are directly related to truck configurations and fuel price. However, as noted earlier BIOTRANS does not consider the effects of truck characteristics and routes on fuel consumption. Overhead (8%), tires (8%), maintenance and repair (7%), interest (6%), and depreciation (6%) are the next most important cost components. A further 10% of cost is made up of road user charges (4%), oil and lubricants (3%), insurance (2%) and registration (1%).

3.3.2 Effects of truck configurations

The effect of six different truck and trailer combinations were examined while holding overhead costs constant (Table 3.2). Different configurations directly affect fixed and variable equipment costs as well as labor costs.

For fixed costs, different configurations have different purchase and salvage costs and machine life that produce different depreciation and interest costs. For example, in BIOTRANS, a 4 axle truck and double trailer results in higher depreciation and interest costs compared to a 3 axle truck and single trailer.

For variable costs, different truck and trailer configuration directly affect repair and maintenance costs and tire costs. There are different numbers of tires and types of tires used with different truck and trailer configurations. In BIOTRANS, a 3 axle truck with single trailer produced the lowest total truck cost while a 4 axle truck with double trailer (40-20’) had the highest total truck cost.

Table 3.2 Transportation costs and productivity for different truck and trailer configurations.

Truck Configurations	Labor ($/Yr)	Overhead ($/Yr)	Trucking ($/Yr)	Total Operation Cost ($/Yr)	Productivity (GT-Miles/Yr)	Trucking rate ($/GT-Mile)
3 axle truck						
Single trailer (53')	24,794	14,300	86,468	125,562	837,000	0.1500
Double trailer (32-32')	27,478	14,300	90,249	132,027	918,000	0.1438
Double trailer (40-20')	27,478	14,300	91,489	133,267	918,000	0.1452
4 axle truck						
Single trailer (53')	24,794	14,300	87,468	126,562	891,000	0.1420
Double trailer (32-32')	27,478	14,300	91,249	133,027	918,000	0.1449
Double trailer (40-20')	27,478	14,300	92,489	134,267	918,000	0.1463

Different trailer configurations directly influenced loading and unloading times. These terminal times can directly affect trip cycle time. Longer cycle times increase the working hours per day and elevate labor costs (Table 3.2). In BIOTRANS, single trailer configurations had lower labor cost than double trailer configurations.

Truck productivity (GT-Miles/Yr) was different with truck and trailer configurations when travel distance was constant. In BIOTRANS, a 4 axle truck with single trailers allowed the transport of more volume than a 3 axle truck, while there was no difference in productivity between 3 and 4 axle trucks with double trailers. Double trailers had higher productivity than single trailers. Consequently, larger payloads produced lower transportation costs when other input variables were held constant (Table 3.2).

Trucking rate ($/GT-Mile) was used to compare truck cost efficiencies in different truck and trailer configurations. In BIOTRANS, a 4 axle truck with single trailer was the most cost efficient truck and trailer type (Table 3.2). Although the 4 axle truck with single trailer has higher operating costs than a 3 axle truck, its higher productivity compensates for the higher operating costs and consequently produces a lower trucking rate than found for a 3 axle truck. However, the optimal truck configuration may depend on the moisture content of the transported material. With low moisture, light material, the four-axle truck with double trailer configuration may be better than the four-axle truck with single trailer configuration because it has a higher volume capacity. In double trailer configurations, a 3 axle truck has a lower trucking rate than a 4 axle truck. This result was due to operating cost alone because productivities between 3 and 4 axle trucks are constant. Double trailers were more cost effective than a single trailer on a 3 axle truck but less cost effective on a 4 axle truck.

3.3.3 Effects of transported materials

Woody biomass comes in a wide variety of forms from hog fuel to sawdust. These materials have very different properties for loading and unloading due to their different load densities. The load density of woody biomass can be defined by what proportion of the load volume is airspace, and what is solid material? Scion (2009) found that the load densities of hog fuel and chip (35 to 45%) were slightly lower than those of sawdust (40 – 45%). However, the load density of shavings was much lower

(20%) compared to other materials. In our study, similar results were found; the payload of shavings was 24 GT per load while other materials had 34 GT per load for a double chip van configuration (Figure 3.3). In addition, the different properties of the materials may also affect loading and unloading times. In Chapter 2 we reported that hog fuel has significantly shorter average loading and unloading times than other materials due to it particle size and relatively high water content.

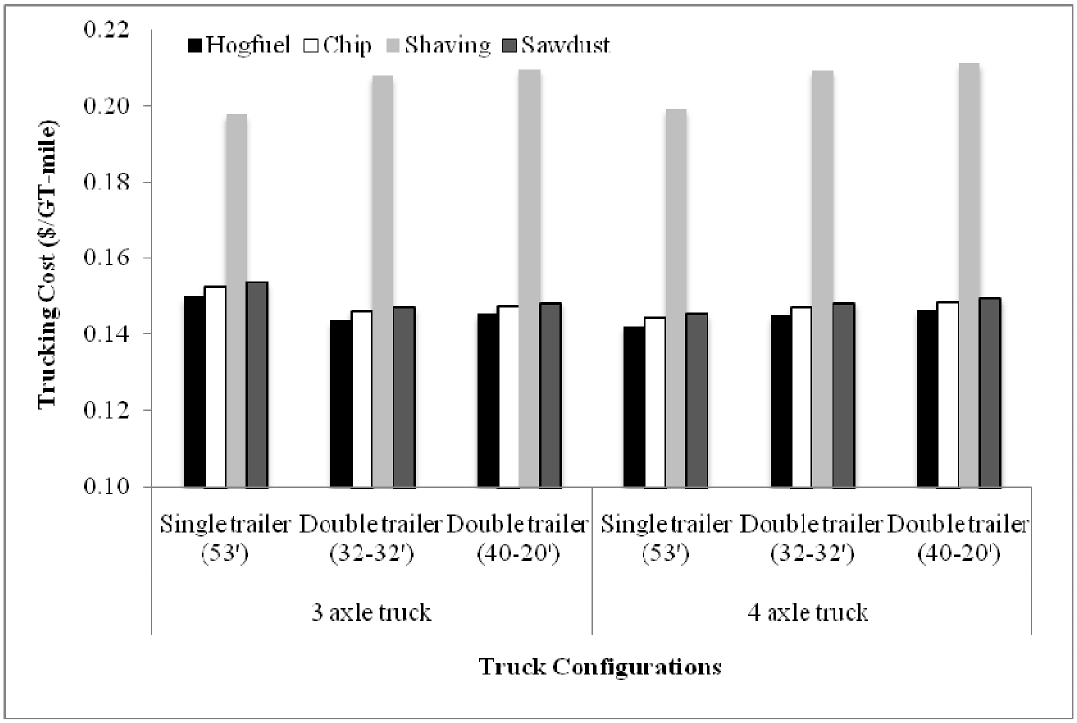


Figure 3.9 Trucking costs with different types of woody biomass

The differences in payloads and loading and unloading times among types of woody biomass directly affect total trucking costs. As shown in Figure 3.9, shavings have about 30% higher trucking costs than other material types. This is due to lower payloads and longer loading and unloading times. However, the low moisture content for shavings may produce higher revenue than other materials if energy conversion plants use a payment system based on bone-dry-ton (BDT). This may compensate for the high trucking cost. In other materials, hog fuel has the lowest trucking costs compared to chip and sawdust but these differences are not statistically significant at the $p = 0.05$ level.

3.3.4 Effects of travel distance and route

Travel distance has the major influence on transportation costs. Travel route is the major factor determining trucking costs when travel distance is constant. To find the effects of travel distance and route on transportation costs, three different types of travel route were generated by different compositions of road class. The routes were defined as follows:

Worst: 5 percent of freeway, 5 percent of highway road having good grade and few bends, 50 percent of highway having adverse grades and many tight curves, and 40 percent of urban road.

Basic: 25 percent of freeway, 25 percent of highway road having good grade and few bends, 25 percent of highway having adverse grades and many tight curves, and 25 percent of urban road.

Best: 50 percent of freeway, 40 percent of highway road having good grade and few bends, 5 percent of highway having adverse grades and many tight curves, and 4 percent of urban road.

The test was examined for a situation with only one load per day by a 3 axle truck with a single trailer. Figure 3.10 shows the expected costs per GT and GT-Mile, respectively, for a range of transportation distances on three different travel routes. As expected, transportation cost ($/GT) increased with increasing travel distance while trucking rate ($/GT-mile) decreased. Trucking rate rapidly decreased with increasing travel distance up to 100 miles of one-way distance and then it decreased at a slower rate. Similar results were reported by Grebner et al (2005) for log products transported in the southern USA.

In Chapter 2 we found that road characteristics highly affected overall travel time. Different road classes in the road classification system we used had different travel speeds and travel times. For example, travel speeds on highways were twice as fast as those on roads in urban areas. Road standards were shown to affect transportation costs. As can be seen in Figure 3.10, the worst routes had higher transportation costs and trucking rates than the basic and best routes. In the worst route, long hauls on poor roads and crossing through urban roads contributed to increased total travel time and consequently increased trucking cost and trucking rates. In contrast, lower transportation costs and trucking rate were associated with the best route conditions, mainly resulting from more usage of freeways that had the highest travel speed.

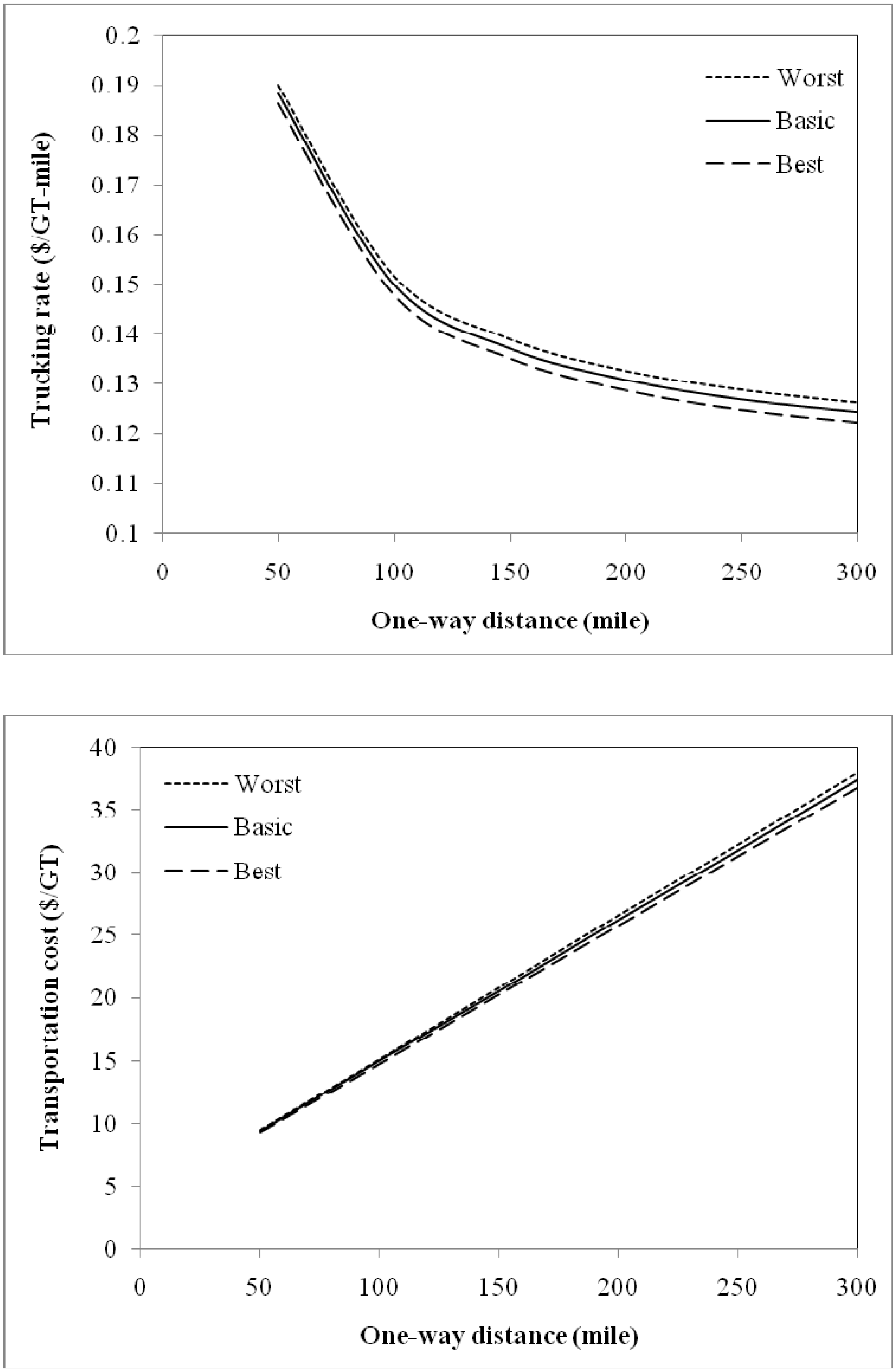


Figure 3.10 The effects of travel distance and road conditions on transportation costs for a 3-axle truck with a single trailer (assuming one load per day)

3.3.5 Effects of back-hauling

In woody biomass transportation, the truck normally returns empty to its previous origin for another load or to their home base. Empty travel, particularly for longer travel distances, is often considered as inefficient performance in transportation cost analysis. Therefore, minimization of such empty travel has been found to be very important in reducing transportation cost. Implementation of backhaul trucking is often considered as one of the least expensive methods for improving transportation costs (Murphy 2003). Backhaul trucking is a transportation method whereby empty trucks pick up another load near the previous unloading place rather than returning empty all the way to the original origin. Backhaul trucking is an excellent method for minimizing empty travel distance and reducing transportation cost. However, its implementation is often limited due to the difficulty of finding another load near the previous unloading place. In our study, backhaul trucking was used on five different routes (Table 3.3). The average one-way distance was 166 mile and next truck loads were located at 1.3 to 35.2 miles from the previous unloading destination. The trucking rate for backhauling situations was almost half of the trucking rate for regular travel (without backhaul). In addition, the usage of backhaul trucking produced substantial savings on transportation cost; as high as 47 percent. The cost savings were expected to come from increased truck productivity. The cost reduction found in our study was similar to the 47 percent reduction reported in New Zealand (Murphy 2003).

Table 3.3 Effects of back-hauling on total transportation costs for five sample routes.

Sample Route	Total one-way distance (miles)	Distance between first conversion plant and second mill (miles)	With back-hauling		Without back-hauling		Percent difference in transp. cost (%)
			Trucking rate ($/GT-mile)	Transp. cost ($)	Trucking rate ($/GT-mile)	Transp. cost ($)	
1	164.9	10.2	0.0874	447	0.1597	818	45
2	160.5	15.8	0.0902	449	0.1604	798	44
3	169.4	35.2	0.0950	499	0.1580	830	40
4	160.9	16.2	0.0903	450	0.1603	800	44
5	175.6	1.3	0.0829	451	0.1574	857	47

3.3.6 Sensitivity analysis

3.3.6.1 Sensitivity to changes in fuel price and consumption

Fuel price directly affected total fuel cost ($/yr) and total transportation cost ($/GT-mile). A small movement in price greatly impacts costs and may reduce margins for the owner. The effect of fuel prices on transportation costs is presented in Figure 3.11.

A 10 percent change in fuel price changes total cost by 3.1 percent. With a 10 percent increase of fuel price, the overall fuel cost increased by $4,938 per year per truck. Fuel economy is also related to travel speed. If travel speed is increased, more fuel would be consumed and fuel cost increased. However, an increase of travel speed can reduce total working hours per day and lead to savings in total labor costs.

Berwick and Dooley (1997) reported that transportation costs increased by 2.3 percent as the legal speed limit increased from 55 miles per hour to 60 miles. In our study, a 10 percent increase in speed on all classes of road results in a 4 percent decrease in total transportation costs.

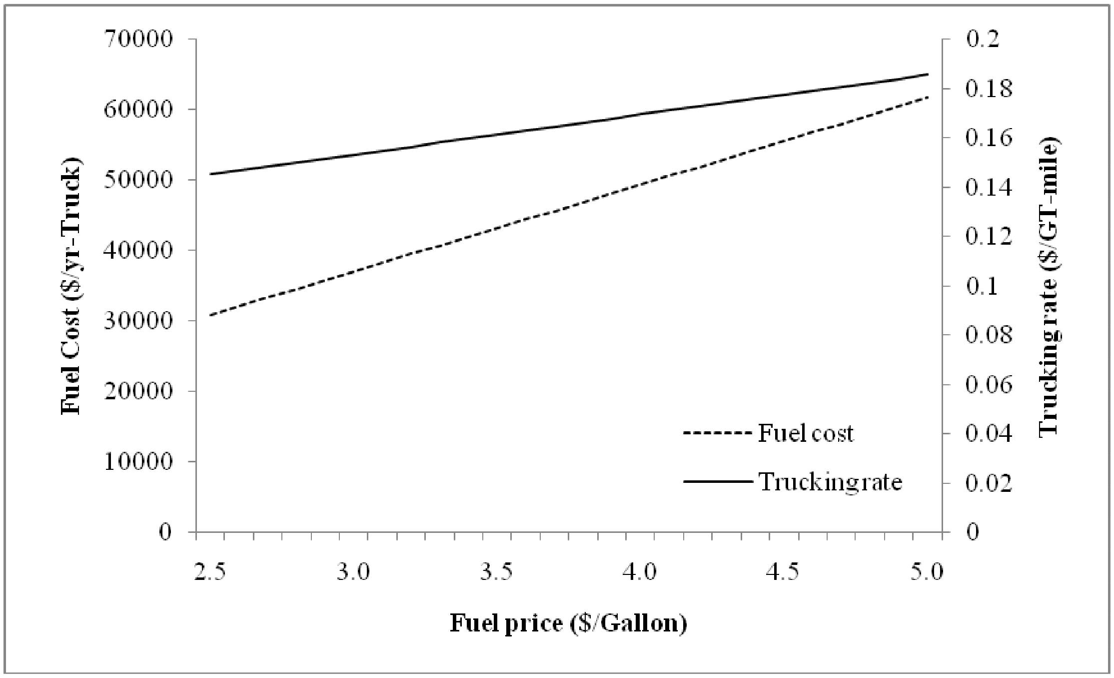


Figure 3.11 The effects of fuel price on transportation costs for a 3-axle truck with a single trailer carrying hog fuel

A fixed fuel consumption rate of 4.4 miles per gallon was initially used in BIOTRANS. The effects of using different fuel consumption rates for different road classes on transportation costs are shown in Figure 3-12. For the analysis, different fuel consumption rates were taken from a report by American Transportation Research

Institute (ATRI 2009). The fuel consumption rates for road classes #9 (HGS), #13 (HDS), and #17 (Urban) were 4.7, 4.5, and 4.0 miles per gallon, respectively. In addition, freeway and other road classes were assumed to consume 4.9 miles per gallon. The urban road class has a considerably higher fuel consumption rate than other road classes because there is more gear changing associated with these roads. The sensitivity analysis relates to one of the routes running between the I-5 freeway and the Oregon coast. The analysis showed that fixed fuel consumption rates produced 3 % higher fuel cost and 1 % higher total transportation costs than using different fuel consumption rates for the selected route.

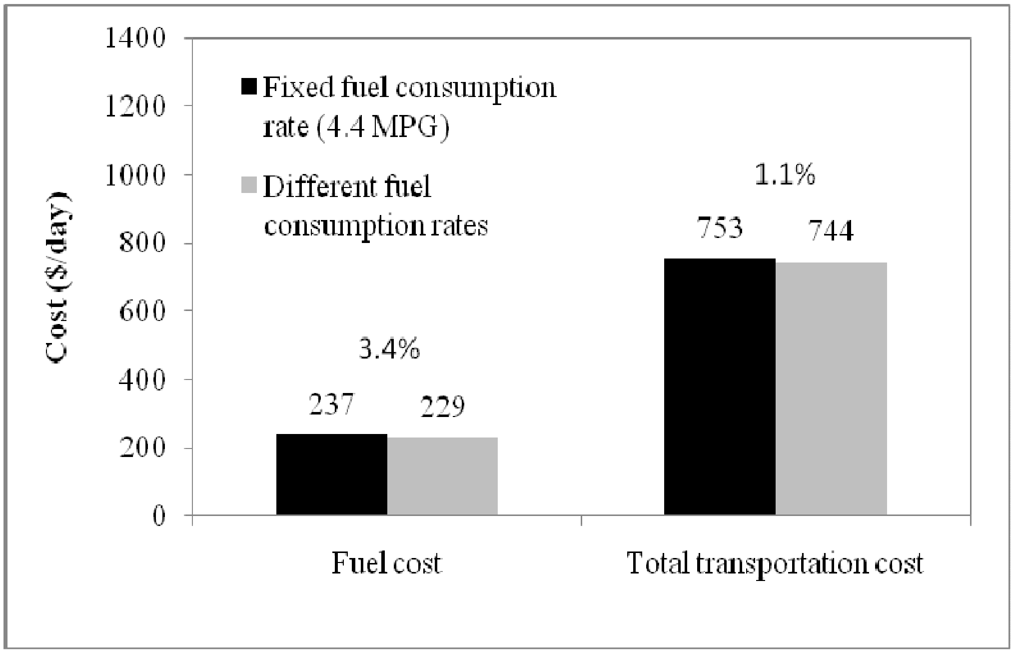


Figure 3.12 The effects of different fuel consumption rates on transportation costs for a 3-axle truck with a single trailer carrying hog fuel

3.3.6.2 Sensitivity to changes in labor cost, maintenance and repair cost, and interest rate

Sensitivity analyses of labor, maintenance and repair cost, and interest are presented in Table 3.4.

Table 3.4 Sensitivity analysis for labor, maintenance & repair, and interest rate on total transportation costs

Variable	10 % increase from base case	Percent increase or decrease in total transportation cost
Labor	$1.40 per hour	+ 3%
Maintenance & repair	$ 0.02 per mile	+1.5%
Interest rate	1%	+ 0.5%

Labor cost, along with fuel costs, is one of the two largest cost components of total transportation costs. The default labor rate in BIOTRANS is $14 per hour. In sensitivity analyses, a 10 percent increase in labor cost changes total costs by 3 percent.

Maintenance and repair costs vary with machine age and utilization. Generally, new equipment has lower maintenance and repair cost while older equipment has higher repair costs. In this study, maintenance and repair cost was set initially as 17 cents per mile. In sensitivity analyses, a 2 cent increase per mile in maintenance and repair cost increases total costs by 1.5 percent. With respect to interest rate, a 1 percent absolute increase leads to a 0.5 percent increase in total transportation costs.

3.4 CONCLUSION

In this study, a trucking production and costing model was developed based on Microsoft EXCEL spreadsheets, to estimate transportation productivity and cost when hauling woody biomass from mills to energy conversion facilities in western Oregon.

Labor (27%) and fuel (28%) were the two largest components of total cost. Therefore, small improvements in these components could significantly reduce the overall truck operating costs.

Different truck and trailer configurations significantly affected transportation costs. A 4 axle truck and single trailer was the most cost efficient hauling configuration. However, the optimal cost effective transportation option may change depending on the moisture content of the transported material types. Double trailers are more cost effective when used with 3 axle trucks than 4 axle trucks.

Different types of woody biomass also influenced total trucking costs due to their different material sizes and payloads that directly influence loading and unloading times. In our study, shavings have 30 percent higher trucking costs than other material types. Compared with chips and sawdust, hog fuel has the lowest trucking costs but the cost differences between these materials were not statistically significant.

The implementation of backhaul trucking appeared to be an excellent way to minimize empty travel distance and reduce transportation cost. However, its implementation is often limited due to the difficulty of finding another load near the previous unloading point.

In the sensitivity analyses, labor, fuel, and maintenance and repair costs were identified as the cost parameters that have the largest potential for woody biomass transportation cost reduction. In particular, a 10 percent increase in fuel cost resulted in a 3 percent increase in total transportation costs.

Understanding of transportation cost structure through simulations of BIOTRANS could help decision makers to indentify cost efficient transportation options that may increase profit or decrease costs. In addition, BIOTRANS can be also used to plan and optimize the woody biomass transportation by allowing the user to vary truck configurations, travel routes and other transportation cost parameters. This improved knowledge for woody biomass transportation will hopefully lead to increased transportation efficiency in the trucking industry and improve the utilization of woody biomass for energy production.

3.5 ACKNOWLEDGEMENTS

The authors would like to thank Terrain Tamers Chip Hauling Company, and in particular Brant D. Boyer, for providing access to their transportation data and their willingness to collaborate in this study.

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CHAPTER 4

SOLVING A WOODY BIOMASS TRUCK SCHEDULING PROBLEM

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4.1 INTRODUCTION

With rising fuel costs and enhanced environmental concerns, biomass energy from a wide range of materials is receiving considerable attention globally as a valuable renewable alternative to the use of finite fossil fuels (Hall 2002). The use of woody materials, in particular, is attracting a great deal of attention for bio-energy production, due to its abundant sources of supply. In addition to bioenergy from specially grown forests, there is the opportunity to use waste material or low value by-products from timber production. In spite of these advantages, woody biomass utilization is not economically attractive as fossil fuel due to the high production costs compared to low market values of this material. Although the U.S government provides substantial government subsidies for biomass to become a viable alternative, high production cost is still an economic barrier to the widespread utilization of woody biomass for energy production (Rummer 2008).

Transportation costs from the sources to the energy plants are a significant proportion of the overall production costs of woody biomass. In past studies, transportation costs account for about 25 to 50 percent of delivered costs depending on hauling distance, load bulk density and moisture content of delivered materials (Angus-Hankin et al. 1995, McDonald et al. 2001, Halbrook and Han 2005, Pan et al. 2008). Therefore, increasing the transportation efficiency of woody biomass should significantly reduce overall production costs. Besides the economic savings, there are likely to be reduced environmental impacts (Palmgren et al. 2004). Development of truck dispatching and scheduling systems has great potential to increase the efficiency of woody biomass transport, as it has for transport of products in many other industries.

In the woody biomass supply chain, transportation is generally done by chip vans since these have been identified to be the most cost-efficient transportation system for this type of material. The main operation is to move woody materials from harvesting sites or sawmills to heating plants, pulp plants or export harbors. Planning for woody biomass transportation is considered to be a complex problem because it has multiple supply and demand points, multiple material types, multiple truck and trailer configurations, and multiple time periods. Currently, woody biomass truck fleets are typically scheduled and dispatched by transport planners based on their local knowledge and experience. For small-sized truck fleets, transport planners can handle the organization of their trucking routes adequately without scheduling aids. With increasing fleet sizes and supply and demand points, however, they often create inefficient and poorly organized truck schedules which may result in long working hours for each truck and long waiting times at loading and unloading places. These inefficiencies increase transportation costs and decrease production. To improve log trucking efficiency, a number of optimal truck scheduling and dispatching systems have been developed and these have reportedly lead to significant reductions of costs and fleet size (Weintraub et al. 1996, Palmgren et al. 2003, Murphy 2003, Gunnarsson et al. 2004, Palmgren et al. 2004, Andersson et al. 2008, and Contreras et al. 2008). Weintraub et al. (1996) developed ASICAM, a heuristics based model for the Chilean log transport sector, and found average reductions of 31% in truck fleet size and 13%

in average working hours and operational costs. In New Zealand, Murphy (2003) implemented a truck route scheduling problem using mixed-integer programming that resulted in potential reductions (25 to 50%) in truck fleet size used by two forest companies. Andersson et al. (2008) developed the decision support system, RuttOpt, using linear programming and standard tabu search methods. In Sweden, use of the RuttOpt model reduced the truck fleet size for a company by about 30% and also reduced the total distance driven by trucks by 8 %. Most of the past forest to mill truck scheduling and dispatching models were developed for conventional log trucks and very few examples in the literature deal with woody bioenergy transportation. One of the few examples is by Ericksson and Björheden (1989) who presented a linear programming model for solving a fuelwood transportation problem.

In transportation planning, it is important to have quick and accurate methods that can assist the planner with detailed routes in such a way that total transportation cost and fleet size are minimized while satisfying a set of constraints. Several algorithms have been developed to solve these types of problems. Bixby and Lee (1998) devised a branch-and-cut algorithm for solving integer linear programming (ILP) formulations of the truck route scheduling problem. Gunnarsson et al. (2004) developed a large mixed ILP model. However, the application of these ILP methods often fails for large-scale problems because computation time dramatically increases with problem size (Contreras et al. 2008). Traditionally, several heuristic approaches have been developed to solve larger problems in reasonable time (Weintraub et al. 1996, Sun et al. 1998, Nanry and Barnes 2000, Lin et al. 2009). Although heuristic approaches may not always guarantee that optimal solutions have been found, they have been the focus of a large number of researchers because of their high efficiency and capability of problem solving especially for large and complex problems. Weintraub et al (1996) and Nanry and Barnes (2000) applied tabu search algorithms to vehicle routing problems. Jayaraman and Ross (2003) and Lin et al. (2009) applied simulated annealing heuristics to truck and trailer routing problems and found that simulated annealing is competitive with tabu search in identifying optimal solutions and in running times. In this paper, a simulated annealing approach is developed to solve the truck scheduling problem for woody biomass transportation.

Simulated annealing can be regarded as a variant of the local search-based heuristic technique in that it is possible to escape from being trapped at a local optimum by accepting worse solutions, with a small probability, during its search iterations. This algorithm is based on the annealing technique used in the metallurgical industry. Annealing is the process in which slow cooling is applied to metals to produce better aligned, low energy-state crystallization (Lin et al. 2009). The optimization procedure of simulated annealing reaches a global minimum mimicking the slow cooling procedure in the physical annealing process.

This study was conducted to solve a truck scheduling problem for transporting woody biomass in western Oregon. The problem was limited to transporting by-products (chips, hog fuel, sawdust, or shavings) from saw-mills to conversion plants (energy or pulp) or harbors for export. In order to obtain solutions within reasonable times, we have applied a simulated annealing approach. The basic objective of this problem is to satisfy the demand for different products at each destination while minimizing transportation costs and total working time for a whole day within constraints related to maximum working hours for labor. To test the quality of solutions, our algorithm was first compared with an actual situation that included scheduling of 50 loads and then tested for a range of different scenarios in a medium size scale problem which included 40 mills, 20 plants, 75 loads per day, 4 product types, 75 trucks, and 6 truck-trailer configurations.

4.2 STUDY METHODS

4.2.1 Problem information

The transportation problem in this paper was limited to transport of woody biomass from origins to destinations satisfying predetermined transportation orders (truck loads) in western Oregon. The transportation information was obtained from Terrain Tamers (TT) located in Dillard, Oregon and related to a one year period between May 2007 and May 2008. At the time of problem development, the company had contracted to deliver woody biomass in the form of hog fuel, chips, sawdust, and shavings from 45 saw-mills to 20 conversion facilities, continuously over a one year period. 75 chip vans were used to carry an average of 100 truck loads per day. Two different truck types (3 axles and 4 axles) and three different trailer types (53’ single van, 32’-32’ double van, and 40’-20’ double van) were used. A total of six different truck and trailer combinations were used depending on the characteristics of the loading and unloading facilities (such as size of saw-mills and conversion plants, and loading and unloading systems), and on weight regulations (bridge capacity) for particular routes. Allowable load capacity in each chip van depended on the truck and trailer configurations used and type of woody biomass carried. Detailed allowable load information was reported in Chapter 3. Travel distances for trips were derived from Oregon Transportation Route Map #7 that specified allowable truck lengths, heights and load capacities for each highway. Distances were also classified into 18 different road classes (see Chapter 2) by vertical and horizontal road alignments. Both travel distances and road classes were used to estimate travel times using travel time prediction models (see Chapter 2). Terminal times including loading and unloading times generally varied with trailer configurations and transported material types. Loading and unloading times were estimated by a terminal time prediction model (Chapter 2). For this problem, cost information was collected through the combination of an interview with a senior manager from TT and use of the costing model described in Chapter 3. Both fixed and variable costs were varied with truck and trailer configurations. Fixed costs components included depreciation, interest, insurance, taxes, overhead, and registration fees. Variable costs components included maintenance and repair, fuel, lubricants, labor, road user charges, and tires. Each truck generally started from TT's depot located in Dillard, Oregon and returned to the depot after finishing work for the day. Truck drivers were limited to 10 hours of driving time per day. However, a small amount of overtime was often allowed to complete tasks at loading or unloading facilities having a long one-way trip distance (> 250 miles) for a single trip. If a truck was used it was considered to be fully loaded and carry a single product type.

4.2.2 Mathematical model

The woody biomass transportation problem was formulated as a mathematical programming model. The objective of the model is to minimize the weighted sum of transportation costs and the total working time subject to constraints on routes, working time and predetermined order requirements. The objective function was calculated, based on truck types, woody biomass types, total travel distance, and loading and unloading times. In this problem, five sets of constraints must be satisfied to find the number of feasible routes. The first constraint for the model specifies that each truck chooses only one feasible route. However, each truck is also permitted to stay at the depot for the whole day, in which case no transportation costs and working hours will be incurred. The second constraint assures that the total working time for each truck must be less than 10 hours. For long one-way distance travel, however, a small amount of overtime is allowed to complete a single load for the whole day. The third constraint guarantees that the predetermined orders are satisfied. The forth constraint ensures that the number of trucks that are used for a given truck type must be less than the available number of trucks for the same truck type. The fifth constraint specifies that the binary variables X_{rij} will be 1 if truck i of truck type r used route j and 0 otherwise.

The mathematical formulation of the problem is shown below.

$$Min \quad \sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} K1(C_{rij}X_{rij}) + \sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} K2(T_{rij}X_{rij})$$

Subject to

$$\sum_{j=1}^{M_{ir}} X_{rij} = 1 \qquad r = 1, 2, \dots Y; \quad i = 1, 2, \dots N_r \qquad (1)$$

$$T_{rij}X_{rij} \leq 10 \qquad r = 1, 2, \dots Y; \quad i = 1, 2, \dots N_r; \quad j = 1, 2, \dots M_{ri} \qquad (2)$$

$$\sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} AO_{kprij}X_{rij} = RO_{kp} \qquad k = 1, 2, \dots S; \quad p = 1, 2, \dots D \qquad (3)$$

$$\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} X_{rij} \leq N_r \qquad r = 1, 2, \dots Y \qquad (4)$$

$$X_{rij} \in \{0, 1\} \qquad \forall\, r, i, j \qquad (5)$$

where

Y = number of truck types

N_r = number of trucks in truck type r

M_{ri} = number of feasible routes for truck i of truck type r

S = number of supply points (Sawmills)

D = number of demand points (Plants or harbors)

RO_{kp} = required orders that are transported from supply point k to demand point p

AO_{kprij} = quantity delivered from supply point k to demand point p by truck i of truck type r using route j

C_{rij} = cost of route j used by truck i of truck type r

T_{rij} = working hours of route j used by truck i of truck type r

X_{rij} = Binary variables; 1 if truck i of truck type r used route j and 0 otherwise

$K1$ = weight factors for minimizing the total transportation cost

$K2$ = weight factors for minimizing the total working hours

In our model, the objective function consisted of two different goals; minimizing total trucking costs and total working hours. Minimizing one goal does not necessarily lead to minimization of the other goal. Without weights, costs influence the objective function value by a ratio of approximately 70:1.

4.2.3 Simulated annealing algorithm

4.2.3.1 Initial solution

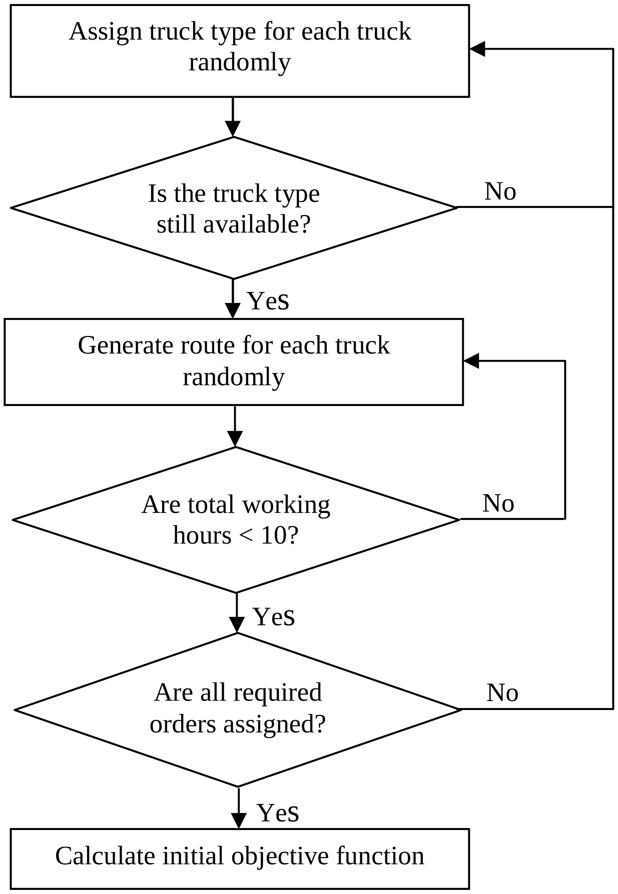


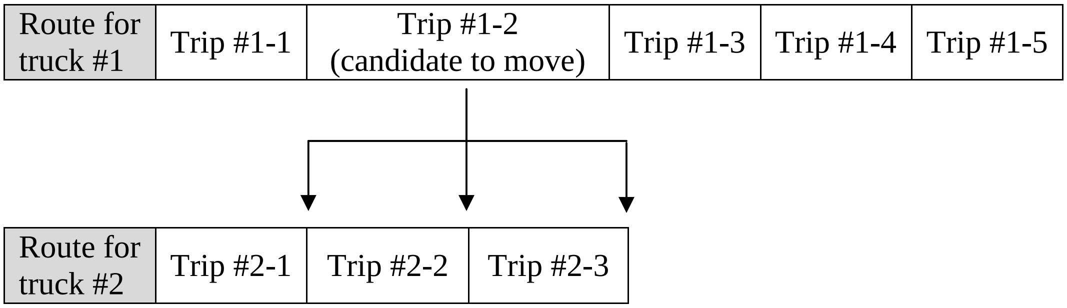
Figure 4.1 Flowchart to calculate initial objective function for the simulated annealing procedure

A simulated annealing (SA) algorithm was used to solve the woody biomass transportation problem. The SA algorithm started by finding a random initial solution (Figure 4.1). In the initial solution procedure, the algorithm first randomly assigned a truck type for each truck from the available truck type list and determined if the truck type is still available to work. If it is still available, the algorithm randomly generated a route for each truck and tested if the working time for the route is within 10 working hours. After generating a feasible route for each truck, the algorithm determined if predetermined orders are fulfilled by all of the trucks. If it is satisfied, the algorithm calculated the initial objective function value.

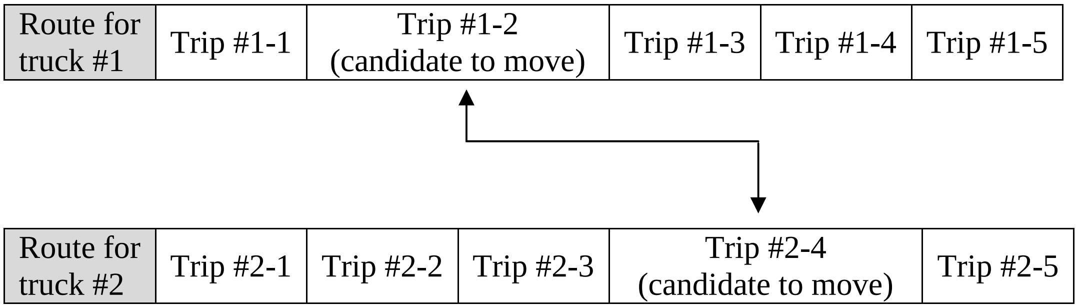
4.2.3.2 Move neighborhoods

After the initial solution was constructed, three different move neighborhoods are randomly employed to generate candidate routes for randomly selected trucks (Figure 4.2).

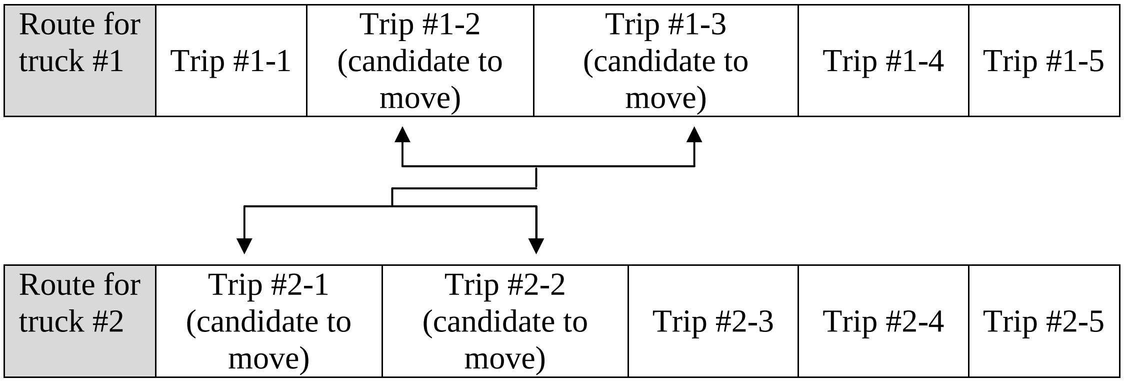
The first attempt to move neighborhoods is single load insertion. The strategy of this method is to move a single load from its current truck route to another truck route in the feasible solution (Figure 4.2-a). The insertion was carried out by randomly selecting two trucks and inserting a randomly selected single load from the first selected truck route to the second selected truck route. The insertion point was also randomly selected in the second truck route. In neighborhood searching methods, the



(a) Example of single load insertion



(b) Example of swapping single pair between routes



(c) Example of swapping multiple pairs between routes

Figure 4.2 Neighborhood search methods

single load insertion has been often used in past truck scheduling programs (Nanry and Barnes 2000) because this method has the greatest potential to minimize the objective function value and truck fleet size used for a whole working day by reducing the number of routes.

The second move neighborhood is to swap a single load pair between two different truck routes (Figure 4.2-b). The swap is performed by randomly selecting two trucks and swapping a randomly selected single load pair between the two different routes. This method is often used to improve new feasible solutions when any single load insertion is not applicable in the current solution.

The last move neighborhood is to swap multiple load pairs between two different truck routes (Figure 4.2-c). The algorithm randomly selects the number of pairs to swap and exchanges selected pairs at randomly selected places between two different routes. This search method is especially helpful when several loads are present for each truck or when the volume of truck scheduling is large (Nanry and Barnes 2000).

4.2.3.3 Simulated annealing procedure

After finding a random initial feasible solution, the algorithm randomly selected two trucks and generated a candidate route for each truck by using a randomly selected neighborhood searching method (Figure 4.3). After generating candidate routes, the algorithm determined if the candidate route for each truck is feasible. If they are feasible, the algorithm calculated the objective function of a temporary solution for the proposed move. The temporary objective function value was then compared with current objective function value to determine if an improvement has been attained. If there was an improvement, the move was accepted. In addition, an inferior solution also had a small probability of being accepted. The Boltzmann probability function (Z) was used to determine whether to accept a worse solution or not. The Boltzmann function (Z) was calculated following:

$$Z = \frac{1}{exp\ ((O_T - O_C)/kT)}$$

where

O_T = the temporary objective function value

O_C = the current objective function value

k = the predetermined constant

T = the current temperature

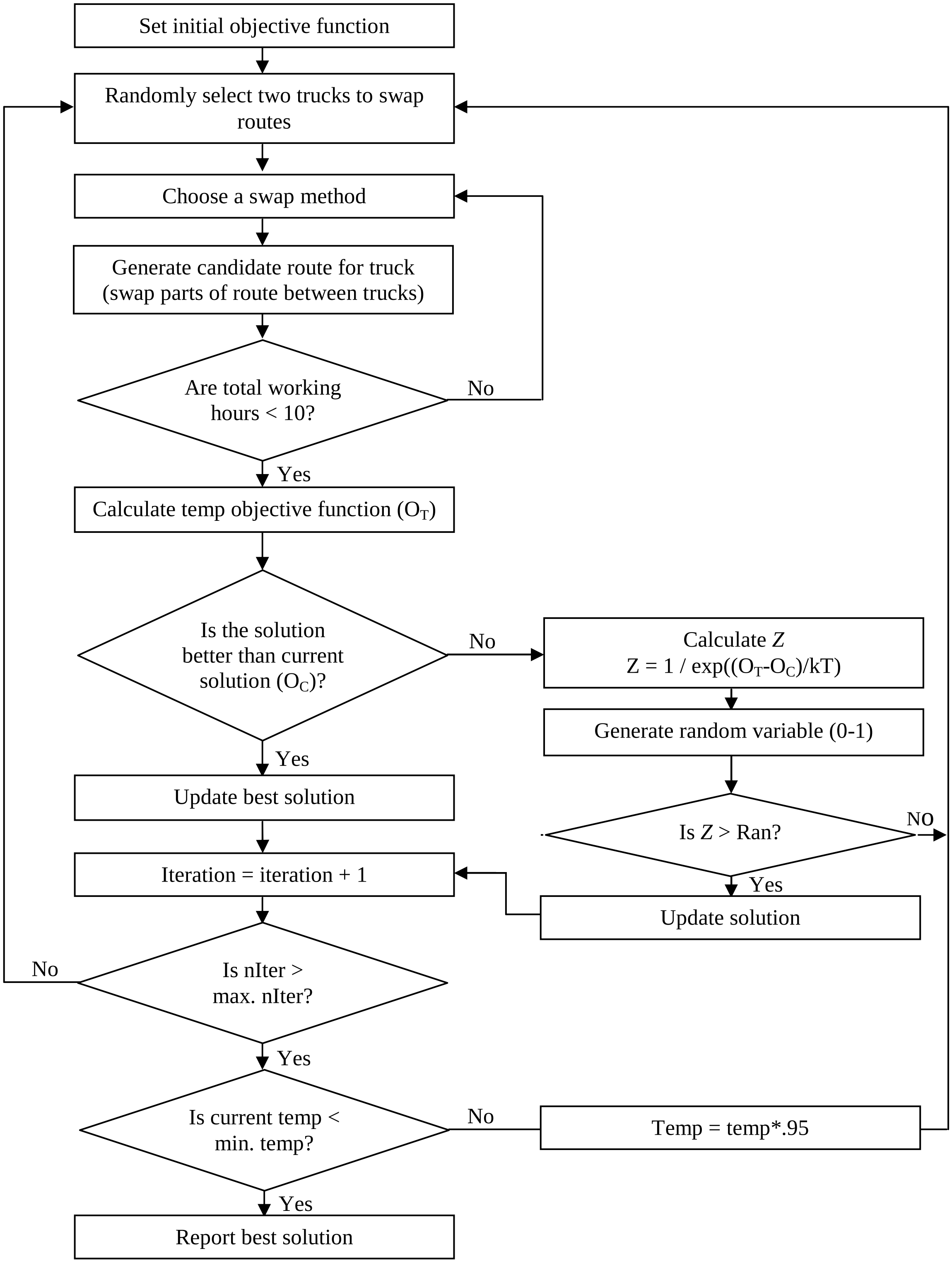


Figure 4.3 Flowchart for the simulated annealing procedure

If the value of Z is greater than a random variable between 0 and 1, the temporary solution will become the current solution even though the temporary solution is bigger than current solution in the case of minimization. In the minimization problem, the essential idea of this procedure is not to restrict the moves to those that only decrease the objective function values, but to also allow moves that increase the objective function values. This algorithm reduces the likelihood of the search being trapped in a local minimum. The search continued for a user-defined number of iterations within each temperature band, at which point the temperature was lowered. The algorithm was stopped when the current temperature was lower than the final user-defined temperature.

4.3 COMPUTATIONAL RESULTS

Our optimal solutions were first compared to the randomly generated initial solutions and the actual solution for one Terrain Tamers schedule that contained 50 loads all transported by 3-axle trucks with either single or double trailer configurations (Figure 4.4). The initial solutions were very similar to the actual solutions ($p>0.05$). Our optimal solution produced an 18 % reduction in total transportation cost and a 15 % reduction in total travel time compared to the actual schedule. This result gives us some confidence in the results we found for the following comparisons that were made based on simulated problems.

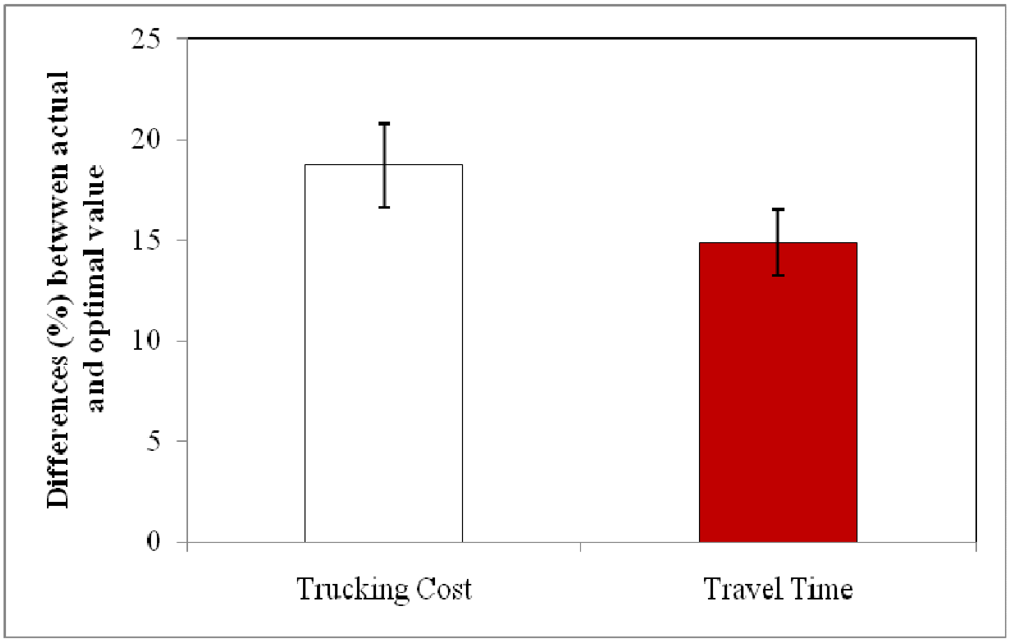


Figure 4.4 The percent differences between optimal solutions and the actual solution for a 50 load problem

Our truck scheduling program for transporting woody biomass was also applied in four different case problems to test the quantitative improvements of solutions and the efficiency of the solution procedures. Each of the case problems included a base case scenario and modifications of selected factors around the base case. Two of the factors related to variations in the truck scheduling problem and two related to variations in the solution procedure. The case problems were generated to evaluate the effects of (1) different sizes of predetermined orders, (2) different sizes of the transportation study area, (3) different weighting levels in the objective function, and (4) different numbers of iterations in the search algorithm. The basic case was built based on the actual transportation tasks carried out by a current trucking company

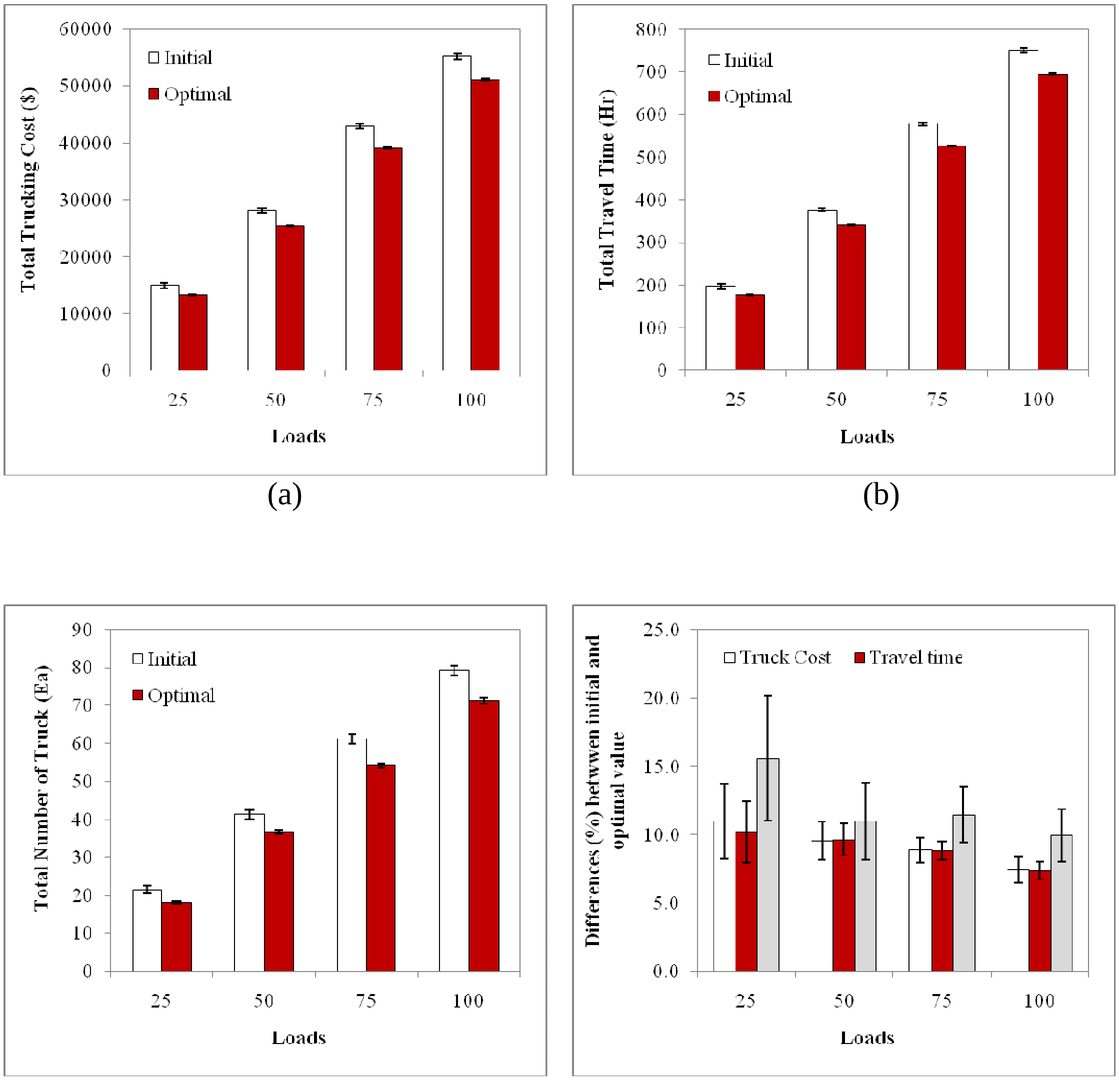
(Terrain Tamers in Dillard, Oregon). In the base case, we assumed that a total of 75 trucks with a total of six different truck and trailer types (two different truck types and three different trailer types) were available to satisfy the total predetermined orders. For each trailer type, ten 3-axle trucks and fifteen 4-axle trucks were available. Forty-five supply points (sawmills) and 20 demand points (conversion plants or export harbors) that are scattered around western Oregon and southern Washington were used in the base case. The predetermined order included a total of 75 truck loads. Trucks were limited to a maximum of five loads per day in the analysis. Maximum working hours were set at 10. In the SA procedures, the initial and final temperatures were set at 10 and 0.1, respectively. The coefficient controlling the cooling scheme was 0.95 and the number of iterations at each particular temperature was 1000. The simulated annealing algorithm was implemented in Visual Basic Application (VBA) for Microsoft Excel. It was then run on a Pentium IV 2.0 GHz PC with 3 GB RAM under Microsoft Windows XP operating system.

The optimization was repeated 25 times for each case problem. The final solution values were compared with the randomly assigned initial solution values for each repetition. Average improvements in solution values, based on 25 repetitions, were calculated for each case problem. Efficiency in solution procedures was measured by the number of seconds required to solve the problem.

Problem 1. Different sizes of predetermined orders

The purpose of this problem was to analyze the effects of different sizes of predetermined order (as measured by total truck loads) on the total objective function value and on the truck fleet size needed. For this problem, the algorithm was tested for four sizes of predetermined order: totals of 25, 50, 75, and 100 truck loads. Weighting values (K1, and K2) were both set at 1 for this problem.

As expected, the initial and optimal function values increased with increasing order sizes (Figure 4.5-(a) and (b)). For all order sizes, the truck scheduling model produced significant improvements in solution values. The average reductions in transportation cost were 7 to 11% for the 100 and 25 truck load orders, respectively (Figure 4.5-(d)). In addition, the truck scheduling model produced an average reduction of 10% in total travel time (Figure 4.5-(d)). The model was better at reducing the truck fleet size than reducing transportation costs and travel times. The highest reduction in the fleet size was 15% for the 25 truck load order, although this improvement was not significantly different to improvements found for the other order sizes ($p>0.05$, Figure 4.5-(d)). Based on the small standard errors found for the 25 replications for all four order sizes, we can say that our scheduling model is likely to produce very good solutions in truck scheduling problems. The model is also efficient; using 1000 iterations for each particular temperature, all of the optimal solutions were obtained within 27 seconds.



(a) (b)

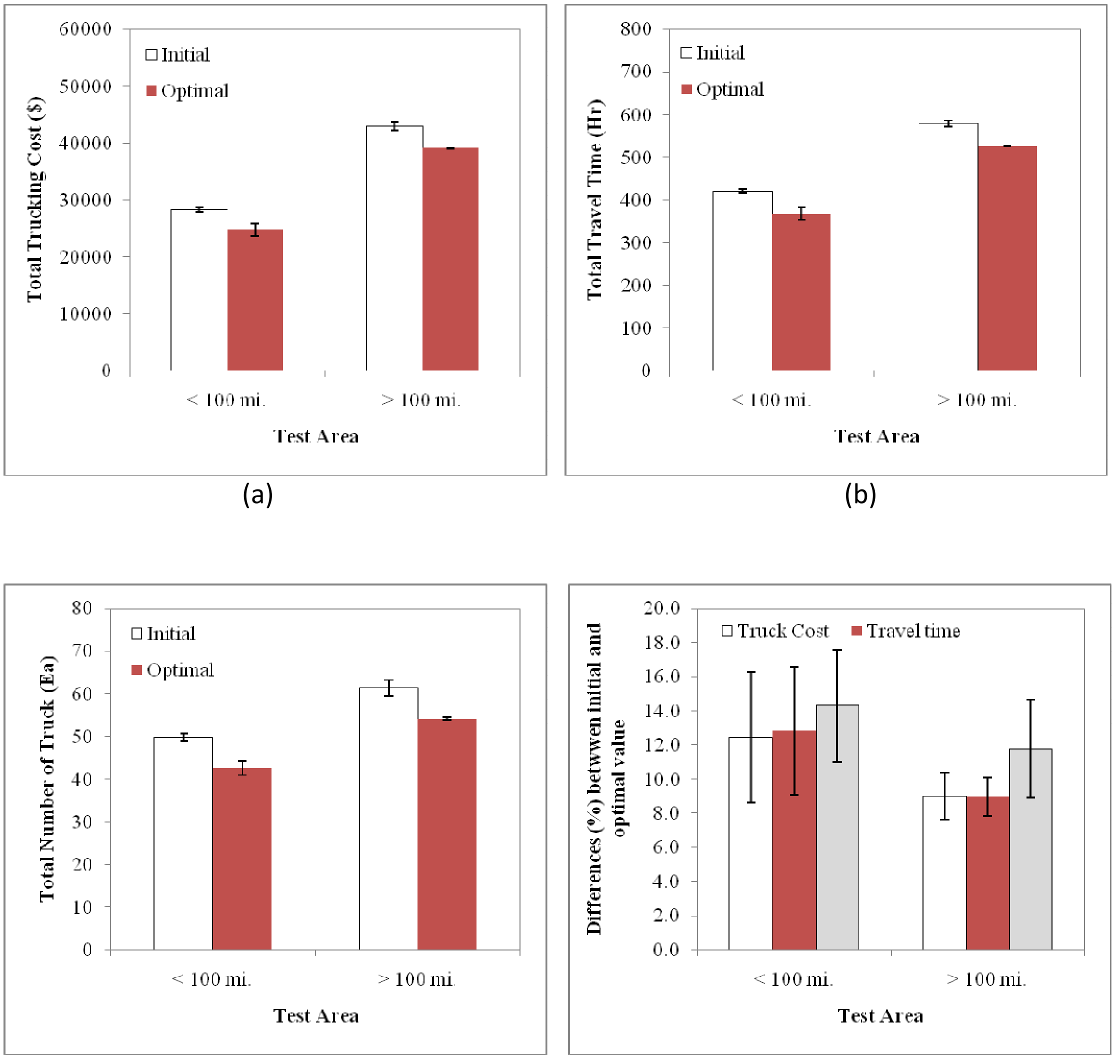
(c) (d)

Figure 4.5 Effect of different total order sizes, as measured by total number of truck loads, on (a) total trucking cost, (b) total travel time, (c) total number of trucks required, and (d) percentage improvements in solution values. Initial values relate to a randomly assigned initial feasible solution. Optimal values relate to the best feasible solution found by the search procedure.

Problem 2. Different size of study area in truck scheduling problem

The purpose of this problem was to investigate the quantitative improvements in optimal solutions due to different sizes of truck scheduling study area. To test this, two study area sizes were developed based on information obtained from the TT trucking company. The first scenario represents that all of the origins (sawmills) and destinations (plants or harbors) located within a 100 mile radius of the truck depot. A predetermined order size of 75 truck loads was assumed. Up to 75 trucks were available for assignment to the order. The second scenario was performed on origins and destinations within a 233 mile radius of the truck depot. Two-thirds of the 75 truck loads were delivered within the 100 mile radius from the truck depot, while the other one-third of loads was transported to locations more than 100 mile radius from the truck depot. Weighting values (K1, and K2) were both set at 1 for this problem.

As expected, the objective function values increased with the increase in size of the study area. Total transportation cost in the first scenario (smaller study area) was $24,975 and in the second scenario (larger study area) $39,258 (an increase of $14,283) (Figure 4.6-(a)). The analysis indicated that the model was more effective in reducing total transportation costs and working hours, as well as fleet size, in the small study are than in the large size study area (Figure 4.6-(d)). These results could be explained by the shorter empty travel distances between truck depot and origins, between origins and destinations, and between destinations and truck depot in the smaller area than the larger area. In this problem, about 70 percent of the total origins



(a) (b)

(c) (d)

Figure 4.6 Effect of two different sizes of dispatching area on (a) total trucking cost, (b) total travel time, (c) total number of trucks required, and (d) percentage improvements in solution values. Initial values relate to a randomly assigned initial feasible solution. Optimal values relate to the best feasible solution found by the search procedure.

and destinations were located within a 100 mile radius of the truck depot. Therefore, in the small size of truck scheduling area there may been have more chances to schedule multiple loads for each truck and back-hauling of loads within the limited working hours. The importance of back-hauling was also noted by Murphy (2003). He reported significant reductions for both trucking costs (up to 47 %) and truck fleet size (20 to 50%). In contrast, many of the trucks within the larger truck scheduling area were limited to a single truck load within the working hour constraint due to the long empty travel distances. Some loads within the predetermined order needed a relaxation of the working hours constraint to carry out the tasks. These specific circumstances limited improvements in the objective values. The average solution time for the small size study area was 21 seconds while the average solution time for the large size study area was 26 seconds.

Problem 3. Different weight levels within the objective function

Five different sets of weight levels were tested to find their effects on optimal values. Levels for K1:K2 ratio ranged from 100:1 to 1:100; the first weight being applied to truck costs and the second weight being applied to working hours. As noted above, without weighting, there are almost two magnitudes of order difference in the contribution of costs towards the objective function compared with working hours (~70:1). The effects of these weighting level extremes is, therefore, to place a very high (~7000:1) overall weighting on costs, when K1 = 100 and K2 = 1, and an almost equal weighting on costs and working hours (~70: 100), when K1 = 1 and K2 = 100.

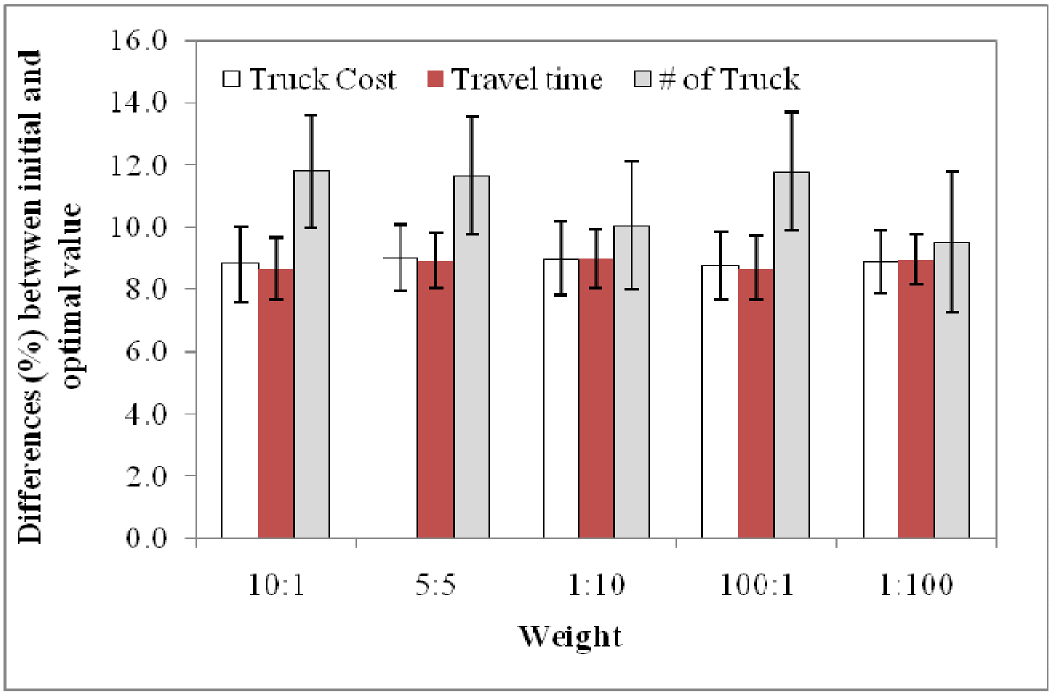


Figure 4.7 Differences between initial and optimal values with different objective weighting levels on total trucking cost, total travel time, and total number of truck. 10:1 means that a weighting factor of 10 is applied to truck costs and 1 is applied to working hours.

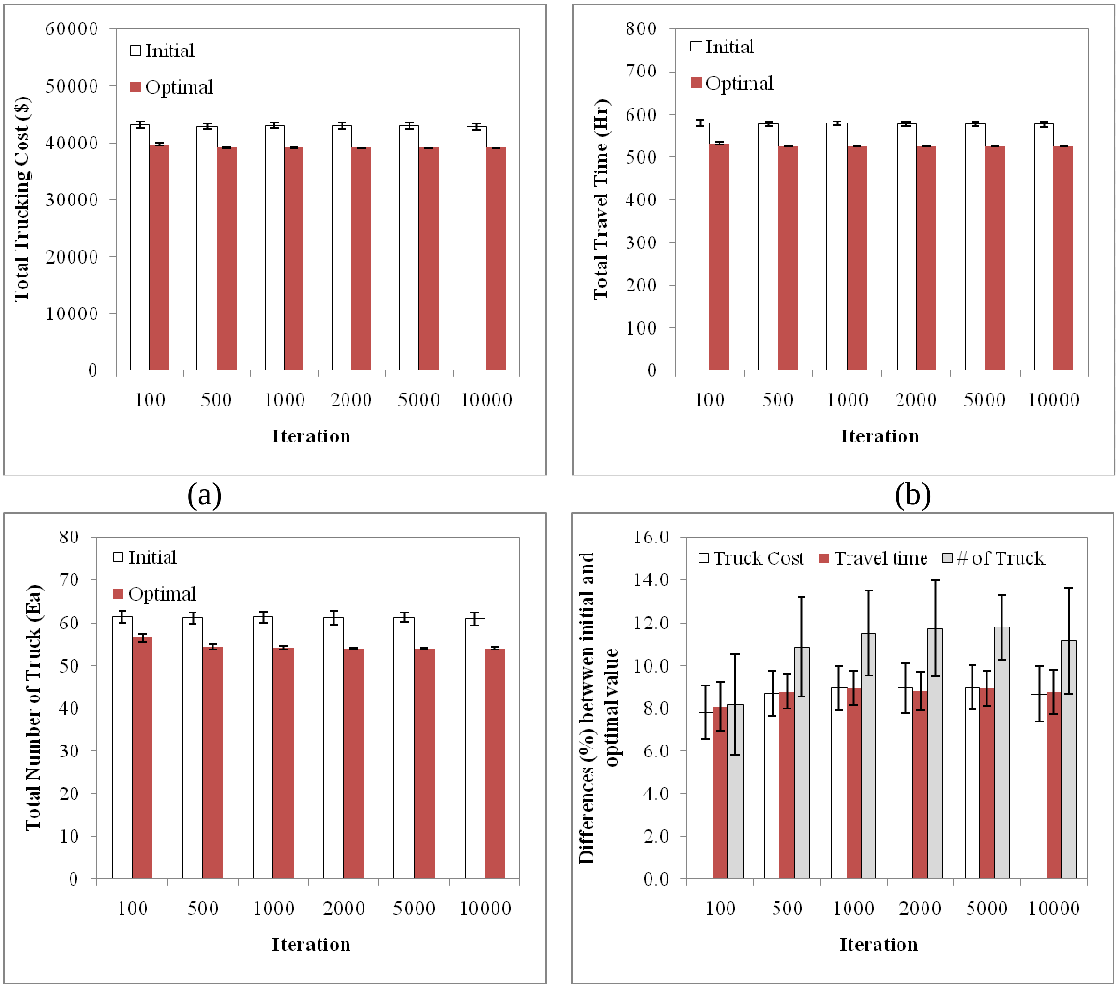
For different ratios in weights, we found that there were no significant differences in optimal transportation costs and working hours as well, as the number of trucks to be used ($p>0.05$, Figure 4.7). When the weight factors were forced more towards minimizing transportation costs the reduction of truck fleet size was 2%

greater than when the weight factors were forced more towards minimizing working hours, but this difference was not statistically significant. There were no differences in solution times between different weight levels within the objective function. The average solution time was 29 seconds.

Problem 4. Different numbers of iterations

In simulated annealing procedures, the number of repetitions at each temperature often has a significant impact on the quality of the solutions. In past studies more iterations have resulted in better solutions (Boston and Bettinger 1999, Contreras et al. 2008). Large problems may need more running time to find optimal solutions. It is important, therefore, to find the appropriate number of iterations needed to obtain good quality solutions within reasonable running times.

In this problem, six different numbers of iterations (100, 500, 1000, 2000, 5000, and 10000) were investigated to find their effect on objective function values. In our results, lower optimal solution values were found with increasing numbers of iterations, but there was no statistically significant difference found between the solution values ($p>0.05$, Figure 4.8-(a) to (c)). All of the iteration numbers produced similar improvements in solution value, except for 100 iterations. Those runs with iteration values of 100 produced significantly lower gains in values than the other five iteration numbers ($p<0.05$) (Figure 4.8-(d)). The program running time was increased



(a)

(b)

(c)

(d)

Figure 4.8. Effect of number of iterations on (a) total trucking cost, (b) total travel time, (c) total number of trucks required, and (d) gain in solution values.

with increasing number of iterations. In particular, iteration values of 10,000 dramatically increased running time up to 800 seconds compared to other iterations but it was also a reasonable running time to obtain optimal solutions (Figure 4.9).

From our results, we recommend that 500 iterations at each temperature would be appropriate to obtain reasonable optimal solutions with a quick running time.

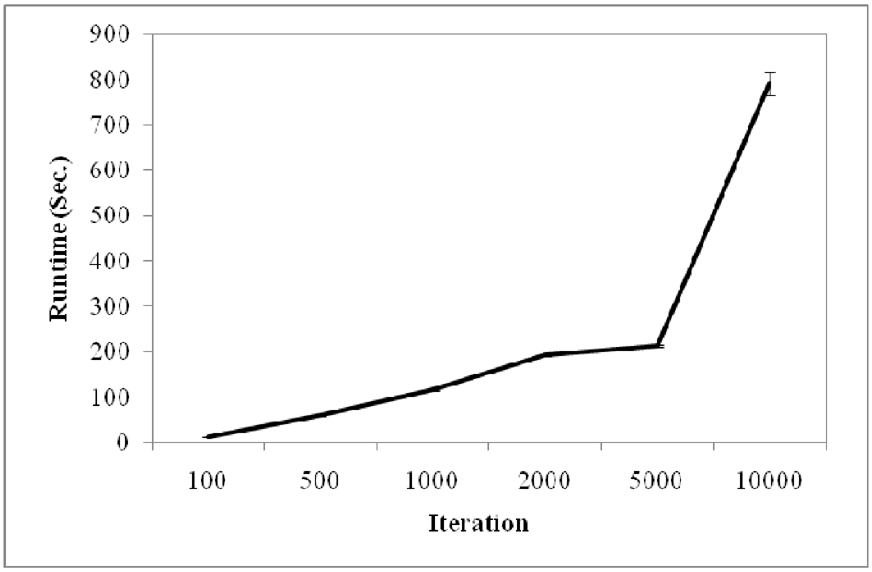


Figure 4.9. Effect of number of iterations on solution run time.

4.4 CONCLUSION

This study was performed to solve a truck scheduling problem for transporting woody biomass in western Oregon. The study was limited to transporting byproducts (chip, hogfuel, sawdust or shavings) from saw-mills to conversion plants (energy or pulp) or harbors for export. A simulated annealing approach was used in order to obtain solutions within reasonable times. The basic objective of the approach is to minimize total transportation costs and total working time for a whole day while satisfying the demand for different products at each destination.

Optimal solutions were compared to the random initial solution and the actual solution for one Terrain Tamers schedule. Our random initial solutions were very similar with the actual solution. The optimal truck route scheduling model produced an 18 % reduction in total transportation cost and a 15 % reduction in total travel time compared to the actual schedule.

Solution times and improvements were evaluated for four case problems. Solution times varied for all of the case problems except problem looking at changes in weights in the objective function. Quantitative improvements in solutions were found for all of the problems. The average reductions in transportation costs were 7 to 11% for predetermined daily order sizes of 100 and 25 truck loads, respectively. In addition, the scheduling model produced an average reduction in total travel time of 10%. The model was better in reducing the fleet size than in reducing transportation costs and travel times. The highest reduction in fleet size was found to be 15% for a predetermined order level of 25 truck loads per day, although this improvement was not significantly different from improvements found for other order levels.

The size of the area serviced by the trucking fleet affected the level of improvement obtained by using the simulated annealing approach to truck scheduling. The algorithm was more effective in reducing total transportation costs and working hours as well as truck fleet size in small areas than it was in large areas.

Applying different weighting factors to trucking costs and working hours in the objective function produced no significant differences in optimal values. Weighting could, therefore, be ignored. Lower optimal solution values were found with increasing numbers of iterations in this minimization problem, but there was no significant difference between the solutions found for different iteration values ($p>0.05$). With respect to improvements over initial feasible solution values, 100 iterations produced significantly lower improvements than were obtained for higher numbers of iterations ($p<0.05$). Therefore, 500 iterations at each temperature would be appropriate to obtain reasonable optimal solutions with reasonable running time.

There are a number of limitations associated with this study. First, our optimization program was developed to solve the on-highway truck scheduling problem for transporting woody biomass residues from sawmills to customers. Further research needs to be extended to the truck scheduling problem for transporting forest residues from harvesting areas since there are different travel conditions on forest roads and different loading operations at harvesting sites compared to those found when transporting the mill-residues on highway. Second, newly designed truck and trailer configurations that can improve the limited accessibility of conventional chip vans to forest areas should be added in the future model. Third, in our current program, working hours were limited to 10 hours of working time per day. However, some single trips had one-way trip distances that were greater than 250 miles and needed over 10 hours to complete the loading, travel and unloading tasks. Further work is needed on how best to deal with the relaxation for the working hours constraint. Finally, linking current transport optimization programs with GIS to estimate travel times and to present final optimal routes to users has been shown to be beneficial for log transportation (Andersson et al. 2008). This feature was not available with our program but should be considered for further development since it should help users to better manage their chip truck fleets.

Despite these limitations this truck scheduling system produced solutions to medium scale transportation problems (up to 100 trucks) in reasonable times (expected time for 500 iteration problem) and could lead to improvements in the economics of woody biomass transportation.

4.5 ACKNOWLEDGEMENTS

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CHAPTER 5

A REVIEW OF THE POTENTIAL APPLICATION OF COLLABORATIVE TRANSPORTATION MANAGEMENT (CTM) IN THE WOODY BIOMASS TRANSPORTATION INDUSTRY

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5.1 INTRODUCTION

In the forest supply chain, problems related to transportation systems have long been an important concern because transportation is the single largest factor of total production costs in United States. In timber production, transportation of logs from the landing to the mill accounts for over 40 percent of total operation costs (Weintraub et al. 1996, Pan et al. 2008). In woody biomass production, McDonald et al (2001) reported that transportation of woody biomass is typically responsible for between 25 and 50 percent of the total delivered costs depending on travel distance. Because transportation makes up such a large part of the overall cost in the forest supply chain, the trucking industry is continuously facing pressures to operate more efficiently. Traditionally trucking companies in the forest field have focused their attention on the development of various transportation equipment types to increase their profitability, i.e., increasing truck capacity or improving the accessibility of trucks on forest roads by improved truck and trailer configurations. More recently, medium and large sized trucking companies have focused their attention on advanced scheduling and dispatching systems to reduce their overall operation costs and fleet size by increasing transportation efficiency.

The development of new equipment configurations has received considerable attention in woody biomass transportation because of limited accessibility by conventional chip vans on forest roads. Conventional chip vans generally don’t track behind the truck very well because the pivot point between the truck and trailer is far forward at the fifth wheel. Conventional chip vans, can, therefore, only be used on forest roads which have been designed and constructed with wider curves than those designed for the stinger-steered log trucks which are typically used for log transportation in the forest. To solve these problems, Sinclair (1985) described a container system to recover woody biomass from mountainous terrain. He found that this system has good potential to haul chunks and short logs from landings and roadside debris accumulations in the forest. Webb (2002) introduced the log/chip B-train vehicle which was capable of hauling both chips and logs and could improve chip and log truck utilization. In recent years, the U.S. Forest Service has designed a stinger-steered chip van. It is combines features from a regular logging trailer and a cargo container and can access the same forest roads as a conventional logging truck. This is considered to be a better alternative than constructing or reconstructing forest roads for conventional chip vans since there are lower investment costs associated with converting existing trailer systems to stinger-steered chip van configurations.

Another on-going effort to improve the efficiency of transportation is the development of optimal truck dispatching and scheduling systems. Weintraub et al. (1996) developed ASICAM, a heuristics based model for the Chilean log transport sector, and found average reductions of 31% in truck fleet size and 13% in average working hours and operational costs. In New Zealand, Murphy (2003) implemented a truck route scheduling problem using mixed-integer programming that resulted in reductions (25 to 50%) in truck fleet size used by two forest companies. Palmgren et al (2003) developed the decision support system, RuttOpt, using linear programming and standard tabu search methods. In Sweden, use of the RuttOpt model reduced the truck fleet size for a company by about 30% and also reduced the total distance driven by trucks by 8 %. However, despite such benefits from improved transportation systems, advanced truck dispatching and scheduling systems have been slowly implemented in the Northwestern U.S. timber supply chain because timber transportation services are often supplied by small and medium sized trucking companies. These typically schedule and dispatch trucks based on local experience and may not consider that they can obtain the same benefits from optimal scheduling systems that large trucking companies can obtain.

Collaborative transportation management (CTM) has recently been put forward as a new opportunity for improving the efficiency of transportation systems. In the forest trucking industry, supply and demand sites are often geographically dispersed within regions that are served by more than one trucking company. There is a high potential for collaboration in supplying transportation services. It is important for companies to work together to eliminate inefficiencies in the transportation process, reduce operating costs, and ensure excellence in the movement of products. Currently, however, collaboration between two or more trucking companies is rare even though they may be located in the same region and ship their products to the same markets or retailers. If they share their shipping information and their trucks, the total fleet size required to haul their products could potentially be decreased, thereby reducing costs. Audy et al. (2007) found that the average cost saving, through utilizing a CTM system in a Canadian wood supply chain, was 4.55 percent and the average reduction in travel distance was 7.25 percent.

Trucking companies will typically participate in a CTM system when each company can obtain greater benefits from their collaboration than they could obtain when they operate individually. However, although CTM can produce substantial cost savings for the group, it does not always provide significant cost savings for individual companies within the group. Therefore, it is important to build an agreement between the participants for efficiently managing the group’s efforts and equitably sharing the benefits to ensure the long-term stability of the collaboration (Audy et al. 2010).

A number of recent studies have addressed cost allocation methods and frameworks for an efficient implementation of CTM. Frisk et al. (2010) used a case study that included eight forest companies, to examine a new cost allocation method. Their method was based on sharing relative profits as equitably as possible among the participants. Audy et al. (2010) explained how to efficiently build and manage profitable logistics collaborations and how to share their profits.

In this chapter, we (1) review the general establishment of a collaborative transportation coalition, discuss how the leadership of the coalition can be assumed and look at how participants in a coalition are selected, (2) look at the benefits of CTM based on studies external to and within forest industries, (3) discuss how to share cost savings and present some examples of cost/saving allocation methods from the literature and (4) explore the potential implementation of CTM in the woody biomass transportation industry.

5.2 ESTABLISHMENT OF A COLLABORATIVE TRANSPORTATION COALITION

In the trucking industry, the interest in CTM has risen with increasing competition from countries with low production costs, mainly China, and escalating environmental concerns. The main objective of CTM is to improve the operating performance of all entities involved in the relationship by eliminating inefficiencies in the transportation component of the supply chain through collaboration. In business, collaboration occurs when two or more companies form a coalition and exchange or share information and resources with the goal that their collaboration will generate benefits that they cannot generate individually.

In the building of collaborative transportation systems, the forms of collaboration between organizations vary with the nature of the information shared as well as the degree of interaction between partners. In general, the level of information sharing increases with the degree of collaboration. The opportunities to add potential benefits can also be increased with the degree of interactions between partners. Esper and Williams (2003) and Audy et al. (2010) described the extension of value contribution by collaboration as the collaborative network expands and information sharing increases. If partners choose to adopt a simple form of collaboration, sharing only transactional information such as orders and payments, the benefits contributed by collaboration can be limited to improving efficiencies in contract negotiations. However, if they decide to agree on a partnership collaboration or consortium collaboration that shares strategic and tactical information such as customer demand, forecasts and operational capacities, the benefits to be added by collaboration would be more significant. These additional benefits would typically come from improved shipment and carrier management and enhanced fleet routing and scheduling systems. For example, wood bartering and backhauling between partners in a wood supply chain are typical executions of strong partnership collaboration. Wood bartering can be used in such a way that destinations between supply and demand nodes are changed (Frisk et al. 2010). Exchanging of timber volumes through sharing supply/demand information between partners can reduce transportation costs. Backhauling is a transportation method by which a truck carries one or several loads while returning to the base area where its first load originated (Palander et al. 2002). This effort in transportation has long been used in individual trucking companies in order to reduce both transportation costs and empty vehicle movements. In southern Sweden, Carlsson and Ronnqvist (1998) found that backhauling would make it possible to reduce transportation cost by up to 4.6% and the distance driven with empty loads by around 21%. They also noted that the economic efficiency of backhauling especially increased when it was combined with collaboration.

To build collaboration between partners, one or a set of the players typically has the leadership of a coalition. Leaders of the coalition may lead the collaboration, deciding who should be admitted and how benefits should be divided. The leadership of the relationship will usually vary with the business context and the size of the partners involved in the collaboration. Their contribution and organization objectives will also significantly influence the leadership (Audy et al. 2010). Audy et al. (2009) have identified six different types of leadership currently used for collaborative transportation (Table 5.1). These are classified by the different objectives and attitudes of the leaders, and can be generalized to other logistics collaborations. Audy et al. (2009) also investigated the impact of different behaviors of the leader in collaboration through the use of case studies. Audy et al. (2007) introduced the importance of the leader's behavior in the collaboration and demonstrated how the leader's behavior in a coalition can affect the costs/saving allocation among the partners as well as the development and the size of the coalition.

In the building of collaboration, the selection of one or more partners to be admitted into a coalition is a difficult task, requiring care, because not all partners contribute positively to a coalition. Some partners may enter with a lot to provide and little to gain while others can benefit greatly with little to offer (Audy et al. 2010). In business, the right partner is the one who has a similar organization size, technologies, culture, and philosophy. In addition, partners must have similar goals and objectives for the coalition and be ready to share the benefits as well as the risk in a trustful partnership (Liu et al. 2006). Deciding on the number of partners is also an important task if the collaboration is to work effectively. Typically, large-sized collaborations have more opportunities to gain great benefits than small-sized collaborations.

However, the former is usually associated with an increase in transactional costs as well as in the complexity of cost and saving allocations between participants in a coalition (Audy et al. 2010). Therefore, the small-sized collaboration may be preferred due to these increased problems.

Table 5.1 Six different types of leadership for collaborative transportation management (Audy et al. 2009)

	Description of the leadership
1	A customer leads the collaboration: It aims to minimize its transport costs by finding other customers that can provide a good equilibrium (geographical, volume, and time) between supply and demand.
2	A carrier or third-party logistics (3PL) leads the coalition: It aims to maximize its profit by a better usage of its carrying capacity.
3	A forth party logistics (4PL) provider leads the coalition: It aims to minimize/maximize the costs/profit of its partners.
4	Customers share the leadership of the coalition: They aim to minimize their transportation costs.
5	Carriers share the leadership of the coalition: They aim to maximize their profit by a better usage of their carrying capacity.
6	Carriers and customers share the leadership of the coalition: They aim to minimize their transportation costs by using the carrying capacity of the carriers

5.3 COST SAVINGS WITH CTM

Collaboration among trucking companies has been identified as a powerful approach to improve delivery routes, provide more competitive transportation rates and reduce hidden transportation costs. Cost savings by collaboration between partners in number of industries have been identified through case studies. In many of these case studies, the savings are defined as the difference between the cost of the collaborative plan and the sum of the cost of each individual plan (Audy et al. 2007). Cruijssen and Salomon (2004) analyzed the effect of collaboration for an entire coalition and report that cost saving may range from 5 to 15% and can be higher. In 1999, Wal-Mart piloted a collaborative transportation management project with Procter & Gamble and J.B. Hunt to improve the efficiency of transportation. They found that there was a 16 percent decrease in unloading time and a 3 percent drop in empty miles (Dutton, 2003). Krajewska et al. (2007) analyzed the profit margins resulting from horizontal cooperation between two freight carriers. They found that the cooperation yielded a 10% reduction in the number of vehicles used and a 12.5% reduction in transportation cost. Cruijssen et al (2007) examined the effect of average order size in the collaboration. They reported that collaborative planning appears to be more profitable in sectors where there are many small orders than in sectors where the average order size is large.

In the forestry field, the importance of a collaborative transportation system has been introduced by several past studies. Palander and Väätäinen (2005) examined the potential benefits from collaboration in a wood supply chain in Finland. They found a 20 % reduction in transport costs with collaboration between the partners when backhauling was used and a 2% reduction in costs without backhauling. Audy et al. (2007) also found cost savings through use of a collaborative transportation system, albeit somewhat smaller (4.55 %) than those reported by Palander and Väätäinen (2005). An average reduction in travel distance of 7.25 percent was also reported by Audy et al. (2007). In Sweden, Frisk et al. (2010) examined the potential transportation costs savings for eight forest companies when a CTM system was used. Savings of up to 14% in the transportation cost were identified. They also identified environmental benefits resulting from collaboration between companies; namely a 2% reduction of emissions from the trucks.

5.4 SHARING THE COST SAVINGS FROM A COLLABORATIVE TRANSPORTATION SYSTEM

In the building of collaboration, a key question is how the total cost or savings should be distributed or shared among the participants because the level of benefits achieved by each partner may differ. Therefore, it is necessary to build methods that ensure that the right distribution of the benefits among participants make the collaboration acceptable for everyone. Typically, a good cost/saving allocation mechanism should attract trucking companies to the collaboration, enable easier agreements, and help to keep the collaboration together. Several saving/cost allocation methods have been described in the literature (Tijs and Driessen 1986, Young 1994, Audy et al. 2007, Audy and D’Amours 2007, Frisk et al. 2010).

In saving allocation methods, the behavior of the leader is important because the leader proposes the method which will be used to share the benefits of the coalition among the participants. Audy et al. (2007) developed two different saving allocation methods under the different behavior of leading player and tested the effects of the leader’s behavior on saving allocation in a wood supply chain. The first sharing method is the altruistic saving allocation method. In this business model, the leader shares among all the partners the marginal increase in the benefit of coalition produced by adding a new partner. The split of the marginal benefit is based on the stand alone weighted cost of each player in the coalition. The second method is the opportunistic saving allocation method. For this model, the marginal increase in the benefit to the coalition, when a new partner is added, is shared between the leading players and the new partner only.

Frisk et al. (2006) suggested that sharing of the benefit could be addressed by using a cost allocation approach rather than a saving allocation approach. In other words, instead of splitting the savings of the coalition among the participants, the cost of the collaborative planning is split between the participants. They developed three different cost allocation methods, called EPM (Equal Profit Method), which provide an as equal relative profit as possible among the participants and tested them on a case study in forest transportation. The three cost allocation methods used by Frisk et al. (2006) are described below.

1. Proportional equal savings: the cost is allocated so that each player obtains the same percentage of savings; for example, if there are three players each gets one third of the savings. However, the leading players in the coalition may not think this is fair.

2. Weighted volume: the cost is allocated according to the proportion of the player's transport volume of the total volume transported by the coalition. Because transportation costs are often charged on a volume basis, this method was instinctively suggested, and unanimously accepted, by the companies in the case study. This method is also easy to understand and implement.

3. Weighted volume according to the transportation plan: this method is similar to the second method but the difference is that the transportation plan is explicitly taken into account in the cost allocation. In this case, for each delivery route, the cost is spread between the participants using the route according to the volume ratio of their shipments to the total volume shipped on the route.

More recently, Frisk et al (2010) re-evaluated a number of sharing mechanisms, which included economic models based on cooperative game theory (Tijs and Driessen 1986, Young 1994), separable and non-separable costs, shadow prices and volume weights. They also developed more advanced EPM approaches based on modifications of earlier case studies and demonstrated the advantages of using EPM approaches over other approaches.

5.5 POTENTIAL IMPLEMENTATIONS OF CTM IN A WOODY BIOMASS SUPPLY CHAIN

In woody biomass supply chains, large volumes and relatively long transport distances together with the low market value of the material transported make it important to improve the transportation efficiencies. Sources and sinks for woody biomass within a region are often served by more than one trucking company. In many cases, volumes of the same or similar assortment are transported in opposite directions by two different trucking companies due to a low level of interaction between the trucking companies. There is, therefore, generally a high potential for collaboration within woody biomass supply chains. CTM between two or more companies could provide substantial opportunities to improve the efficiency of transportation. This can be done by exchanging transport material and backhauling between participants in a coalition. In transported material exchanging, volumes of some supply points are exchanged between companies to reduce the total travel distance. Backhauling is used to find better travel routes by combining transport orders of different trucking companies. In wood supply chains, the significant cost saving through these approaches have been reported in several past studies (Weintraub et al. 1996, Carlsson and Ronnqvist 1998, Murphy 2003)

Although the benefits of CTM to the forestry sector have been demonstrated in the literature, it is difficult to directly apply in practice. Because collaboration is likely to depend on such things as who the partners in the coalition are, the resources they bring to the coalition, the order in which they join the coalition, their business goals, agreements on how the benefits are to be shared, the region in which the coalition is being operated, the types of woody biomass materials to be transported, etc. there is not a single solution, or model, that will solve all CTM problems.

Collaboration involves sharing of information, efficient utilization of shared transport resources, and optimal allocation of the benefits. A new framework to achieve this will be needed. The sharing of information is likely to involve the development of a web-based collaborative network system that is also used to effectively carry out the collaborative transportation planning between participants in a woody biomass supply chain. This web-based system could consist of three different processes. The first process would include importing the transportation data such as orders (volumes to be delivered between supply and demand points), the number of trucks available, and other information related to work performances by participants. The second process would define truck routes using optimal truck scheduling and dispatching systems based on the transportation data. The last process would present the output (travel routes) for each participant.

A simplified version of the optimal truck scheduling infrastructure for a non-CTM system has been presented in the Chapter 4 of this thesis. The optimization model would have to be modified for a CTM system. Modification of the objective function would depend on the benefit sharing method that was agreed upon between coalition participants. As a demonstration of how our model could be modified, let us assume that one of the EPM approaches described by Frisk et al. (2010) is used. The objective function of the EPM method is to minimize the maximum difference in pairwise relative savings. The mathematical formulation of the optimal collaborative truck scheduling problem is now shown below:

$$Min \quad f$$

Subject to

$$f \geq \left| \frac{AC_a}{SC_a} - \frac{AC_{a'}}{SC_{a'}} \right| \qquad \forall\, a, a'$$

$$SC_a \geq AC_a \qquad a = 1, 2, \ldots P$$

$$\sum_{a=1}^{P} SC_a - \sum_{a=1}^{P} AC_a \geq 0 \qquad a = 1, 2, \ldots P$$

$$SC_a = \sum_{a=1}^{P} \sum_{r=1}^{Y} \sum_{i=1}^{N_r} \sum_{j=1}^{M_{ri}} K1(C_{arij} X_{arij}) + \sum_{a=1}^{P} \sum_{r=1}^{Y} \sum_{i=1}^{N_r} \sum_{j=1}^{M_{ri}} K2(T_{arij} X_{arij})$$

Note that SC_a is calculated by running Phase I *P* times for *P* individual companies.

$$AC_a = \sum_{a=1}^{P}\sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} K1(C_{arij}X_{arij}) \; + \sum_{a=1}^{P}\sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} K2(\,T_{arij}X_{arij})$$

Note that AC_a is calculated by running Phase II one time for *P* individual companies.

$$T_{arij}X_{arij} \leq 10 \qquad a = 1, 2, \dots P \;;\; r = 1, 2, \dots Y \;;\quad i = 1, 2, \dots N_r \;;\; j = 1{,}2, \dots M_{ri}$$

$$\sum_{a=1}^{P}\sum_{r=1}^{Y}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} AO_{akprij}X_{arij} \;=\; RO_{kp} \qquad a = 1, 2, \dots P; \quad k = 1, 2, \dots S; \quad p = 1, 2, \dots D$$

$$\sum_{a=1}^{P}\sum_{i=1}^{N_r}\sum_{j=1}^{M_{ri}} X_{arij} \;\leq N_{ar} \qquad a = 1, 2, \dots P; \quad r = 1, 2, \dots Y$$

$$\sum_{j=1}^{M_{ir}} X_{arij} = 1 \qquad a = 1, 2, \dots P \;; \quad r = 1, 2, \dots Y \;; \quad i = 1, 2, \dots N_r$$

$$X_{arij} \;\in \{0, 1\} \qquad \forall\; a, r, i, j$$

Where

Y = number of truck types

N_{ar} = number of trucks in truck type r owned by comapany a

M_{ri} = number of feasible routes for truck i of truck type r

S = number of supply points (Sawmills)

D = number of demand points (Plants or harbors)

RO_{kp} = required orders that are transported from supply point k to demand point p

AO_{akprij} = quantity delivered from supply point k to demand point p by truck i of truck type r using route j owned company a

C_{arij} = cost of route j used by truck i of truck type r owned company a

T_{arij} = working hours of route j used by truck i of truck type r owned company a

X_{arij} = Binary variables; 1 if truck i of truck type r owned company a used route j and 0 otherwise

$K1$ = weight factors for minimizing the total transportation cost

$K2$ = weight factors for minimizing the total working hours

SC_a = Stand alone cost for participant a before a coalition found in Phase 1

$SC_{a'}$ = Stand alone cost for participant a' before a coalition found in Phase 1

AC_a = Cost allocated in participant a in a coalition found in Phase 2

$AC_{a'}$ = Cost allocated in participant a' in a coalition found in Phase 2

P = number of participants in a coalition

A flowchart for a collaborative transportation optimization model, which uses simulated annealing (SA) to solve the optimal collaborative truck scheduling problem, is shown in Figure 5.1. The optimization algorithm has two Phases. In Phase I the stand alone optimal costs for individual participants could be obtained using the procedure described in Chapter 4. In Phase II the initial objective function is set to 1, which means that improvement for the coalition have yet to be determined. The costs allocated to individual participants in a coalition are calculated after swapping routes between participants. If the overall costs from a coalition's solution are higher than the sum of the costs of individual participants the swapped routes are unacceptable and a new set of routes to be swapped is selected. If the coalition's solution is acceptable the relative savings for each participant are calculated. The relative savings of participant a is expressed as $(SC_a – AC_a) / SC_a = 1 – (AC_a / SC_a)$. Therefore, the difference in relative savings between two participants, a and a', is equal to $(AC_a / SC_a) – (AC_{a'} / SC_{a'})$. The temporary objective function value, f, could be then compared with current objective function value to determine if an improvement has been attained. If there was an improvement, the move would be accepted. The following steps would be similar to the simulated annealing procedure presented in Chapter 4.

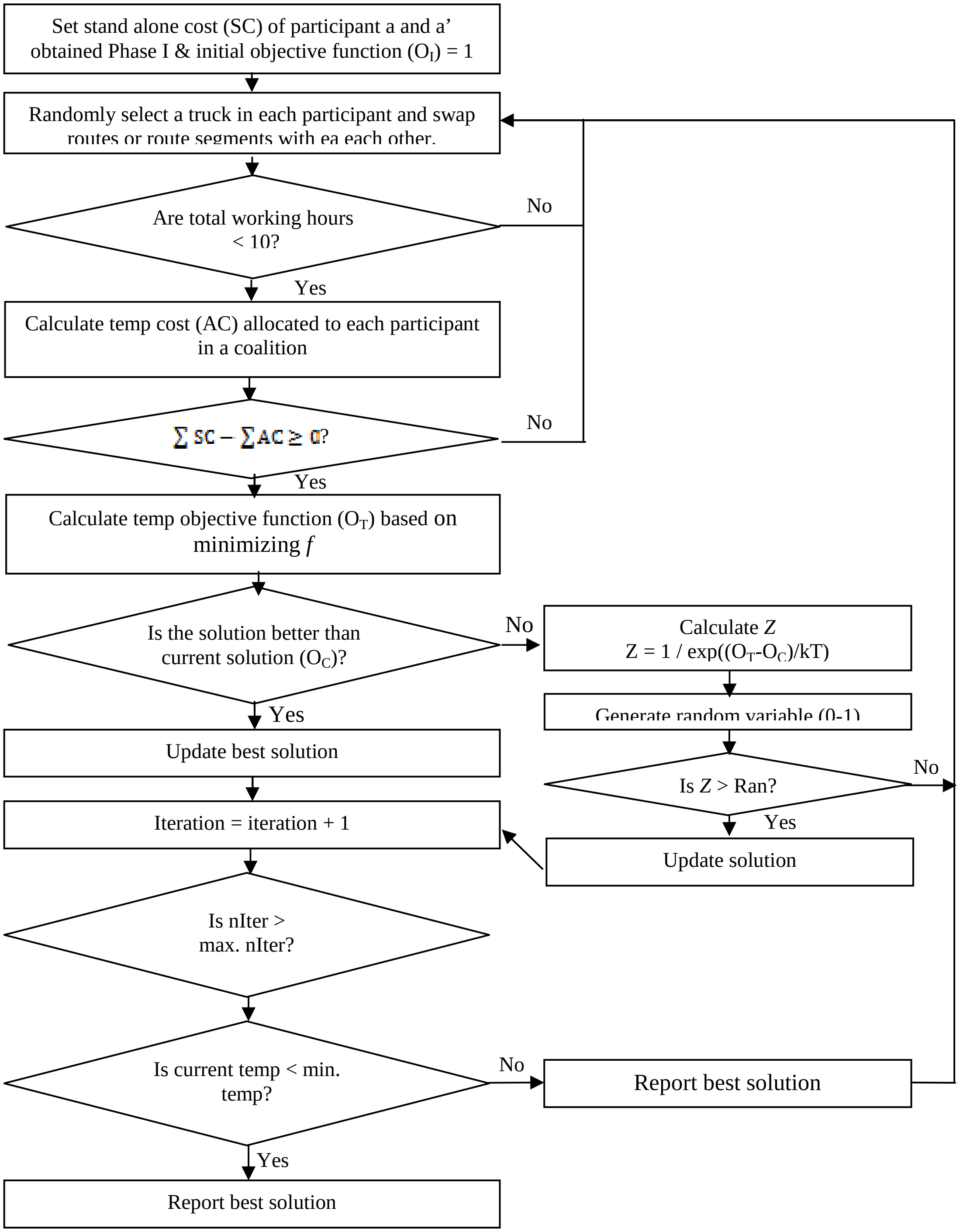

Figure 5.1 Flowchart for the simulated annealing procedure to solve the collaborative truck scheduling problem

Frisk et al. (2010) use costs alone as the basis for calculating their objective function value. We use a weighted combination of costs and time in our model. It would be simple, however, to use costs alone or time alone if the user wished to. This would be a simple matter of setting either the K2 or K1 weighting factors to zero.

An issue that needs to be considered in Oregon and other parts of the US is the antitrust law that prohibits anti-competitive behavior and unfair business practices. Therefore, coalitions that utilize collaborative transportation planning systems must be executed in a way that so that they cannot be regarded as a formation of an antitrust. To overcome this barrier to collaboration there needs to be an independent organization (third-party) to lead the coalition.

5.6 CONCLUSION

In this chapter, we reviewed how to build and manage efficient collaborative transportation systems. The role of the leaders when building collaboration systems was introduced and six different leadership approaches were described. Depending on the business context, collaborative planning created the great potential cost savings; in the range of 5 to 15%. A key issue is how savings should be distributed among the collaboration participants. Two saving allocation methods under the different behavior of leading player and three different EPM methods were described. In the last section, we discussed the potential implementation of collaborative transportation in woody biomass transportation industry and proposed the concept of a web-based collaborative network system for woody biomass transportation based on optimal truck scheduling program presented in the Chapter 4.

Based on this literature review, future work should focus on the development of a web-based CTM system for a woody biomass supply chain. This model should be developed and tested around several case studies. Vital to this work is developing a range of cost/saving allocation algorithms for woody biomass transportation to ensure the right distribution among participants of the benefits obtained by the collaboration.

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CHAPTER 6

GENERAL CONCLUSIONS

Transporting woody biomass from the sources to the energy conversion facilities is the single largest component of the overall supply costs for many suppliers around the world. In woody biomass supply chains, transportation costs are about half of the delivered costs. Since transportation makes up such a large part of the overall cost in the forest supply chain, small increases of the efficiency could significantly reduce the overall supply costs. Therefore, there has been much research continuously invested in not only finding more efficient transportation systems but also developing decision support systems to reduce transportation cost and improve the utilization of wood. However, most of the past research was focused on conventional log transportation in the forestry sector. The literature lacks information about woody biomass transportation from sources to energy conversion facilities. The ultimate objective of this dissertation is to provide new knowledge which leads to improvements in the economic feasibility of using woody biomass for energy through reductions in transportation costs. This study investigated the transportation of by-products (chips, hog fuel, sawdust, or shavings) from saw-mills to conversion plants (energy or pulp) or harbors for export by chip vans travelling on off-forest roads. Results presented in this dissertation may help trucking companies to build the logistic transportation system and management strategies that could reduce transportation cost and produce maximum profits in woody biomass transportation.

Chapter 2 summarized the results of prediction models to estimate not only travel times but also loading and unloading times for transporting wood raw materials in western Oregon and southwestern Washington. In this chapter, travel time was predicted by travel distance over various road classes related to road gradient and alignments. The travel time prediction model developed was shown to be a good predictor for travel time through a validation procedure. From simulations with the prediction model, it was concluded that selecting the routes with shorter urban road distances and longer freeway distances would strongly reduce the travel times. Loading and unloading times were effectively predicted using transported materials and trailer size as the predictors. Prediction models indicated that loading and unloading times of hog fuel and when a single trailer was used were significantly shorter than those of other materials and double trailers, respectively. However, the prediction models produced high, and statistically significant, errors in model validations.

Chapter 3 described the results of the investigation into modeling the effects of different truck configurations, transported material types, and travel route characteristics on transportation costs. In this chapter, a trucking production and costing model (BIOTRANS) was developed to estimate transportation productivity and cost when hauling woody biomass from mills to energy conversion facilities in western Oregon. In the simulations of BIOTRANS based on a base case scenario, it was identified that different truck and trailer configurations significantly affected transportation costs. A 4 axle truck and single trailer was the most cost efficient hauling configuration. However, the optimal cost effective transportation option may change depending on the moisture content of the transported material types. Different types of woody biomass also influenced total trucking costs due to their different material sizes and payloads that directly influence loading and unloading times. Shavings have 30 percent higher trucking costs than other material types. Further examination showed that the implementation of backhaul trucking appeared to be an excellent way to minimize empty travel distance and reduce transportation cost. However, its implementation is often limited due to the difficulty of finding another load near the previous unloading point.

Chapter 4 introduced an optimization program to solve the truck scheduling problem for transporting woody biomass over highways in western Oregon. A simulated annealing approach was used in order to obtain solutions within reasonable times. The basic objective of this algorithm is to satisfy the demand for different products at each destination while minimizing transportation costs and total working time for a whole day within constraints related to maximum working hours for labor. Optimal solutions were compared to the random initial solution and the actual solution for one Terrain Tamers schedule. Our random initial solutions were very similar with the actual solution. The optimal truck route scheduling model produced an 18 % reduction in total transportation cost and a 15 % reduction in total travel time compared to the actual schedule. In addition, four different scenarios in a medium size scale problem were generated to evaluate the effects of (1) different sizes of predetermined orders, (2) different sizes of the transportation study area, (3) different weighting levels in the objective function, and (4) different numbers of iterations in the search algorithm on the quantitative improvements of solutions and the efficiency of the solution procedures. For all order sizes, the truck scheduling model produced significant improvements in solution values within 27 seconds. The average reductions in transportation cost and total travel time were 11% and 10% for the 25 truck load orders, respectively. The model was better at reducing the truck fleet size than reducing transportation costs and travel times. The highest reduction in fleet size was found to be 15% for a predetermined order level of 25 truck loads per day. Further research analysis found that the different sizes of the transportation study area significantly affected the quality of optimal solutions. The algorithm was more effective in reducing total transportation costs and working hours as well as truck fleet size in small areas than it was in large areas. In the effects of different weighting levels in the objective function and different numbers of iterations in the search algorithm on the quality of optimal solution, both scenarios concluded that there were no significant differences in optimal values. However, only 100 iterations produced significantly lower improvements than were obtained for higher numbers of iterations ($p<0.05$). Results suggested that 500 iterations at each temperature would be appropriate to obtain reasonable optimal solutions with reasonable running time.

Chapter 5 summarized the results found in reviewing collaborative transportation management (CTM) that has recently been put forward as a new opportunity for improving the efficiency of transportation systems in the forest trucking industry. The review of literatures concluded that the application of CTM between two or more trucking companies that are located in the same region, ship their products to the same markets or retailers, and share their shipping information and their trucks could eliminate inefficiencies in the transportation process and reduce total fleet size required to haul their products, thereby reducing costs. This chapter also described how to manage the leadership of a transportation coalition and how to select participants for building efficient collaborative transportation systems. In particular, a key issue of CTM was how savings should be distributed among the collaboration participants. To address the questions of this issue, two saving allocation methods under the different behavior of leading player and three different EPM methods were reviewed. The final step of the literature review related to how to implement collaborative transportation in a woody biomass transportation industry. Finally, we proposed the concept of a web-based collaborative network system for woody biomass transportation and presented the optimal truck scheduling problem for a CTM system between two participants. The mathematical formulation of this problem was developed by expanding the optimal truck scheduling model developed in Chapter 4. In this model, the objective function was to minimizing the difference in relative savings between the two participants.

This study strived to address an array of questions related to the logistic transportation system and management strategies for woody biomass transportation from saw-mills to conversion plants on off-forest roads. We recognize that there are a number of limitations in this dissertation.

Firstly, current research efforts in this dissertation were limited to woody biomass supply chains on off-forest roads. Further research needs to be extended to the transportation problem for transporting forest residues from harvesting areas since there are differences in travel conditions on forest roads and loading operations in harvesting sites compared to transporting mill-residues on highway.

Secondly, truck costs and scheduling models were developed from woody biomass transportation data operated in western Oregon and southern Washington. Therefore, it may be difficult to apply the results of this study to other regions which have different woody material characteristics (such as species, water contents and bulk density) as well as different weather conditions and traffic conditions. Further research needs to determine how broadly these findings and considerations can be applied to other regions.

Thirdly, the travel time prediction model that was developed was limited to estimating only loaded travel time. Further work would be needed to estimate more accurate total travel times and costs, although differences in travel speeds between loaded and unloaded trucks carrying forest materials may be less than 10% (B. Boyer 2010 personal communication). In our truck scheduling model, working hours were limited to 10 hours of working time per day. Our research indicated that some single trips having one-way trip distances greater than 250 miles needed over 10 hours to complete at the loading, travel and unloading tasks. Therefore, further work needs to be undertaken on how best to model the relaxation in the working hours constraint.

In the chapter 5, we just reviewed the framework of CTM and proposed the concept of a web-based collaborative network system for woody biomass transportation. Future work should focus on the development of a web-based CTM system for a woody biomass supply chain. Vital to this work is developing a range of cost/saving allocation algorithms for woody biomass transportation to ensure the right distribution among participants of the benefits obtained by the collaboration.

Despite these limitations, it is expected that the knowledge from these studies will lead to increased transportation efficiency in the trucking industry and improve the utilization of woody biomass for energy production.

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APPENDIX

Table A.1 Length (in mile) and classification of road segments along 107 routes from sawmills to energy plants in western Oregon

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	129.0	138.9	158
2	1.9	0.7	1.4	0.0	1.9	0.3	0.5	0.1	22.3	4.2	2.7	0.6	18.3	2.1	2.5	0.6	13.6	42.7	116.5	168
3	0.2	0.0	0.0	0.0	0.7	0.1	0.0	0.0	4.1	0.1	0.0	0.0	6.2	0.1	0.0	0.1	9.3	152.0	172.6	226
4	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	22.3	8.4	104.2	143
5	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	4.9	113.0	120.9	132
6	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	20.3	0.0	0.0	0.0	8.4	0.0	0.0	0.0	14.8	108.0	152.6	208
7	0.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	12.0	0.2	0.1	0.0	15.4	0.1	0.0	0.0	18.9	28.3	76.1	122
8	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	12.7	0.0	86.2	121
9	0.4	0.1	0.1	0.0	3.3	1.1	0.8	0.0	30.3	0.0	1.0	0.1	20.5	3.5	1.0	0.0	10.8	13.9	87.1	109
10	0.5	0.2	0.1	0.0	4.0	0.5	0.8	0.0	28.0	5.7	3.7	0.1	26.3	1.9	1.5	0.0	11.6	2.3	87.4	118
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	30.7	44.5	61
12	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.9	4.7	2.7	0.2	25.7	2.3	1.5	0.0	14.8	8.4	92.2	157
13	0.7	0.3	0.1	0.0	4.0	0.6	0.7	0.0	27.1	4.6	2.7	0.2	27.2	2.2	1.6	0.0	6.9	0.0	78.6	90
14	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	7.4	0.0	0.0	0.0	6.3	0.0	0.0	0.0	8.6	20.1	42.8	60
15	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	8.1	0.0	0.0	0.0	3.2	0.0	0.0	0.0	5.9	13.5	30.9	45
16	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	7.4	0.0	0.0	0.0	6.3	0.0	0.0	0.0	13.1	4.4	31.5	60
17	0.8	0.2	0.0	0.0	2.9	0.0	0.1	0.0	37.4	1.5	0.4	0.0	27.6	0.9	0.5	0.0	15.8	153.3	241.4	284
18	0.7	0.3	0.1	0.0	4.0	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0.0	20.4	82.0	174.2	233
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	129.0	138.9	158

Table A.1 Continued

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
20	1.9	0.7	1.4	0.0	1.9	0.3	0.5	0.1	22.3	4.2	2.7	0.6	18.4	2.1	2.5	0.6	13.6	42.7	116.5	168
21	0.2	0.0	0.0	0.0	0.7	0.0	0.0	0.0	4.1	0.1	0.0	0.0	6.2	0.0	0.0	0.0	9.3	152.0	172.6	226
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	117.7	127.3	161
23	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	5.0	113.0	121.0	132
24	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	22.3	8.4	104.2	143
25	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	20.3	0.0	0.0	0.0	8.4	0.0	0.0	0.0	14.8	108.0	152.6	208
26	0.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	12.0	0.2	0.1	0.0	15.4	0.1	0.0	0.0	24.1	27.6	80.5	129
27	0.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	12.0	0.2	0.1	0.0	15.4	0.1	0.0	0.0	19.0	28.3	76.1	122
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	30.7	44.5	61
29	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.9	4.7	2.7	0.2	25.8	2.3	1.5	0.0	14.8	8.4	92.2	157
30	0.7	0.3	0.1	0.0	4.2	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0.0	14.6	8.5	95.0	135
31	0.7	0.3	0.1	0.0	4.0	0.6	0.7	0.0	27.1	4.6	2.7	0.2	27.2	2.2	1.6	0.0	6.9	0.0	78.7	112
32	0.8	0.2	0.0	0.0	2.9	0.0	0.0	0.0	37.4	1.5	0.4	0.0	27.6	1.0	0.5	0.0	15.8	153.3	241.5	284
33	0.7	0.3	0.1	0.0	4.0	0.6	0.7	0.0	27.1	4.6	2.7	0.2	27.2	2.2	1.6	0.0	6.9	0.0	78.7	90
34	0.7	0.3	0.1	0.0	4.0	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.9	2.5	1.6	0.0	20.4	82.0	174.2	233
35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1	87.3	107.0	142
36	4.8	0.3	0.3	0.1	7.5	0.8	0.6	0.3	44.7	4.7	2.3	0.6	47.1	3.8	4.4	1.8	18.2	0.0	142.1	175
37	0.2	0.0	0.0	0.0	0.6	0.0	0.0	0.0	6.1	0.0	0.0	0.0	9.0	0.0	0.0	0.0	12.4	113.7	141.9	179
38	1.9	0.0	0.1	0.0	2.9	0.3	0.1	0.0	21.3	0.6	0.4	0.2	22.2	0.7	0.5	0.4	7.3	39.6	98.6	148
39	2.8	0.2	0.1	0.0	4.3	0.4	0.2	0.0	37.6	1.6	0.8	0.2	29.7	1.3	0.7	0.4	7.9	4.9	93.0	156
40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	95.6	103.5	127

Table A.1 Continued

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.1	9.5	14.6	32
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	1.3	18
43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5	30.7	40.2	56
44	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	12.7	0.0	86.3	142
45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5	170.0	179.5	225
46	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	2.2	0.3	0.0	0.0	2.6	0.0	0.0	0.0	6.4	42.7	54.4	60
47	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	2.3	0.0	0.0	0.0	4.9	0.0	0.0	0.0	11.5	152.0	171.0	210
48	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	22.0	4.4	99.9	138
49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	4.4	15.3	30
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	30.7	44.5	62
51	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.6	4.7	2.7	0.2	24.6	2.3	1.5	0.0	6.7	0.0	74.3	92
52	0.7	0.3	0.1	0.0	4.2	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0.0	18.8	8.5	99.2	133
53	1.6	0.4	0.2	0.0	3.2	0.5	0.7	0.0	29.9	4.5	3.3	0.4	24.8	1.8	2.1	0.7	9.4	0.0	83.2	128
54	0.7	0.2	0.0	0.0	1.8	0.0	0.0	0.0	11.3	0.0	0.0	0.0	14.6	0.0	0.0	0.0	16.4	130.0	175.0	216
55	6.6	1.6	0.3	0.0	7.6	0.7	0.7	0.0	53.5	7.3	3.5	0.4	55.1	4.5	3.4	0.7	19.8	0.0	165.4	218
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	77.7	87.6	113
57	0.7	0.3	0.1	0.0	1.3	0.4	0.6	0.0	22.6	3.3	2.8	0.3	18.0	1.8	1.3	0.0	2.5	0.0	56.0	67
58	0.7	0.3	0.1	0.0	1.3	0.4	0.6	0.0	22.6	3.3	2.8	0.3	18.0	1.8	1.3	0.0	9.7	8.5	71.6	90
59	0.7	0.3	0.1	0.0	1.3	0.4	0.6	0.0	22.6	3.3	2.8	0.3	18.0	1.8	1.3	0.0	2.5	0.0	56.0	69
60	0.0	0.0	0.0	0.0	2.7	0.2	0.1	0.0	8.8	1.8	0.5	0.1	11.7	2.3	0.9	0.0	4.4	0.0	33.3	43
61	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	12.7	0.0	86.3	118

Table A.1 Continued

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
62	0.4	0.0	0.0	0.0	0.8	0.0	0.0	0.0	6.2	0.5	0.0	0.1	5.4	0.1	0.0	0.2	8.6	152.0	174.3	228
63	0.2	0.0	0.0	0.0	0.6	0.0	0.0	0.0	6.1	0.0	0.0	0.0	9.0	0.0	0.0	0.0	17.6	182.7	216.1	275
64	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	12.7	0.0	86.3	145
65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.2	194.7	208.9	270
66	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	233.7	244.6	341
67	0.9	0.0	0.0	0.0	2.2	0.0	0.0	0.0	12.1	0.7	0.0	0.0	11.8	0.9	0.3	0.0	14.4	25.3	68.6	91
68	0.9	0.0	0.0	0.0	2.2	0.0	0.0	0.0	12.1	0.7	0.0	0.0	11.8	0.9	0.3	0.0	8.6	25.3	62.8	82
69	0.9	0.0	0.0	0.0	2.2	0.0	0.0	0.0	12.1	0.7	0.0	0.0	11.8	0.9	0.3	0.0	11.6	141.0	181.5	236
70	1.6	0.3	0.1	0.0	6.8	0.6	0.7	0.0	39.8	5.5	2.7	0.2	39.1	3.3	1.8	0.0	27.6	54.0	184.0	259
71	0.9	0.0	0.0	0.0	2.2	0.0	0.0	0.0	12.1	0.7	0.0	0.0	11.8	0.9	0.3	0.0	8.6	25.3	62.8	86
72	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.6	4.7	2.7	0.2	24.6	2.3	1.5	0.0	13.6	82.0	163.2	195
73	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.6	4.7	2.7	0.2	24.6	2.3	1.5	0.0	14.3	8.5	90.3	122
74	0.7	0.3	0.1	0.0	3.6	0.6	0.7	0.0	25.6	4.7	2.7	0.2	24.6	2.3	1.5	0.0	7.1	0.0	74.7	105
75	0.9	0.1	0.0	0.0	2.9	0.0	0.0	0.0	36.3	2.6	0.4	0.0	26.9	1.7	0.5	0.0	16.7	31.5	120.6	158
76	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	22.3	82.0	177.8	222
77	0.9	0.1	0.0	0.0	2.9	0.0	0.0	0.0	36.3	2.6	0.4	0.0	26.9	1.7	0.5	0.0	16.7	31.5	120.6	166
78	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	15.8	0.0	89.3	125
79	0.7	0.3	0.1	0.0	4.5	0.6	0.7	0.0	27.7	4.7	2.7	0.2	27.3	2.5	1.6	0.0	22.9	8.5	105.0	144
80	2.8	0.6	1.4	0.1	4.4	0.2	0.3	0.0	48.3	3.1	0.8	0.0	46.0	1.8	1.6	0.0	15.9	0.0	127.2	182
81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.2	55.3	62.5	82
82	0.8	0.2	0.0	0.0	2.9	0.0	0.0	0.0	37.4	1.5	0.4	0.0	27.6	1.0	0.5	0.0	9.9	12.5	94.8	112

Table A.1 Continued

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
83	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.2	55.3	62.5	82
84	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.3	170.0	179.3	212
85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	39.5	43.3	57
86	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	22.8	27.5	43
87	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.2	50.4	59.6	77
88	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	7.4	0.0	0.0	0.0	6.3	0.0	0.0	0.0	13.1	4.4	31.5	45
89	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	7.4	0.0	0.0	0.0	6.3	0.0	0.0	0.0	13.1	4.4	31.5	60
90	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	7.4	0.0	0.0	0.0	6.3	0.0	0.0	0.0	8.7	20.1	42.8	60
91	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	89.8	92.5	116
92	0.7	0.3	0.1	0.0	4.2	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0.0	12.7	0.0	84.6	110
93	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	74.6	81.7	112
94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	0.0	8.2	22
95	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	89.8	92.5	127
96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.5	89.8	98.3	145
97	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	0.0	8.2	20
98	0.7	0.3	0.1	0.0	4.2	0.6	0.7	0.0	26.9	4.7	2.7	0.2	26.8	2.5	1.6	0.0	12.5	0.0	84.4	110
99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5	152.0	161.5	201
100	2.3	0.7	0.1	0.0	1.1	0.1	0.0	0.0	28.0	2.0	0.3	0.2	19.3	1.7	1.5	0.0	8.0	106.0	171.3	182
101	2.3	0.7	0.1	0.0	1.1	0.1	0.0	0.0	28.0	2.0	0.3	0.2	19.3	1.7	1.5	0.0	8.6	32.3	98.3	135
102	2.3	0.7	0.1	0.0	1.1	0.1	0.0	0.0	28.0	2.0	0.3	0.2	19.3	1.7	1.5	0.0	13.8	106.0	177.1	236
103	0.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	12.0	0.2	0.1	0.0	15.4	0.1	0.0	0.0	23.9	27.6	80.4	117

Table A.1 Continued

	Road classes (Miles)																		Total distance (Miles)	Travel time (Min.)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
104	2.8	0.2	0.1	0.0	4.3	0.4	0.2	0.0	37.6	1.6	0.8	0.2	29.7	1.3	0.7	0.4	6.9	4.9	92.0	138
105	0.9	0.2	0.0	0.0	1.4	0.1	0.1	0.0	16.3	1.0	0.3	0.0	7.5	0.7	0.2	0.1	2.0	2.6	33.2	49
106	0.4	0.0	0.0	0.0	0.7	0.0	0.0	0.0	12.5	0.0	0.0	0.0	4.8	0.0	0.0	0.0	8.9	100.1	127.4	155
107	0.9	0.0	0.0	0.0	1.5	0.0	0.0	0.0	18.6	0.5	0.0	0.1	10.1	0.1	0.0	0.2	6.6	17.9	56.6	73