Trucking Productivity and Costing Model for Transportation of Recovered Wood Waste in Oregon

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Abstract

The use of woody biomass has received considerable attention for energy production. However, high production and transportation costs can be a barrier to woody biomass use in some regions. Developing cost-effective transportation systems has become an economically critical issue to expand biomass use. We developed a computer model, named BIOTRANS, to estimate biomass transportation productivity and cost in western Oregon. We used BIOTRANS to evaluate the effects on transportation costs of six different truck configurations, four transported material types, and over 100 travel routes. Different truck configurations, transported material types, and travel route characteristics were found to significantly affect transportation costs. A four-axle truck and single trailer was the most cost-efficient hauling configuration for the conditions studied, and shavings had 30 percent higher trucking costs than other hog fuel, chips, and sawdust.

Woody biomass has great potential as a source of renewable energy in the Pacific Northwest due to the availability of a large and sustainable supply (Perlack et al. 2005). However, high production and transportation costs, compared with relatively low market values, hinder the use of woody biomass. Identifying or developing cost-effective production and transportation systems has become an economically critical issue to expand biomass use.

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 United States. 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-in.) trees for energy. They reported the transportation cost represented 47 percent of the total cost and found transport to be the largest component of the total system costs.

Transportation costs generally vary with particular travel circumstances. Travel distance is the dominant variable determining transportation costs. Up to 60 percent of the delivered costs of biomass can be related to transportation when hauling distances are over 100 miles (Scion 2009). Road conditions such as vertical and horizontal alignments and surface conditions also highly influence transportation costs. Groves et al. (1987) found that travel speeds were strongly related to road class and travel routes, where road classes with poor vertical and horizontal alignments have lower travel speeds and higher hauling costs. The type of material transported can also affect transportation costs. Talbot and Suadicani (2006) reported that low bulk density and high moisture contents can decrease energy densities per load and consequently increase transportation costs.

Understanding of transportation cost structure through simulations with cost models can help identify possibilities for efficiency gains that may lead to increased profits or decreased costs (Casavant 1993). In particular, productivity and costing models enable the user to determine and compare the costs of various hauling options. A number of truck costing models have been developed over the last 70 years. Matthews (1942) described one of the earliest hand-calculated truck rate models for the forest industry. Taylor (1988) described a spreadsheet-based truck costing model that was developed by the New Zealand Logging Industry Research Association. The Forest Engineering Research Institute of Canada developed a computer model to determine the cost of transporting raw forest products from

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the stump to the mill in Alberta (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. Grebner et al. (2005) developed a costing model to evaluate haul routes in the Southeast United States. In the Pacific Northwest, the US Department of Agriculture Forest Service developed a model to estimate production and hauling costs associated with fuel reduction treatments in dry western forests (Biesecker and Fight 2006).

Many of these past transportation cost models are limited in their applicability to biomass transportation and to different regions for a number of reasons. First, many of the past forestry-related cost models were developed for conventional log transportation. If the woody biomass has been comminuted into some form other than logs, for example hog fuel or sawdust, it is generally transported by 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 van configurations often produce limited accessibility on forest roads and the selection of different travel routes compared with conventional log trucks. The grain transport industry uses similar types of vans and has produced production and costing models. In the United States, Berwick and Dooley (1997) developed a spreadsheet simulation model to estimate truck costs for different grain truck configurations, trailer types, and trip movements. The effects of different variables on total trucking costs were examined in their sensitivity analysis. Trimac Consulting Services also created a computerized activity-based model for commercial grain trucking in Western Canada (Trimac Logistics Ltd. 2001).

Second, travel times were often simply estimated based on payload and either one-way or round-trip distance with limited or no consideration of road characteristics and qualities. The implication of this was demonstrated by Groves et al. (1987), who 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 percent between actual and predicted times. The RouteChaser log transport model was one of the exceptions (Grebner et al. 2005). It allowed specification of up to six different road classes. It assumed, however, that a single origin and destination would be repeatedly visited each day within a specified day length.

This study was conducted to understand the cost structures in recovered wood waste (hog fuel, sawdust, shaving, and chips) transportation from sawmills 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 recovered wood waste and also to evaluate the effects of different truck configurations, transported material types, and travel route characteristics on transportation costs.

Methodology

We developed a spreadsheet-based truck productivity and cost model for woody biomass transportation using Microsoft Excel. The model was named the Biomass Transportation Model (BIOTRANS). In BIOTRANS, truck productivity and cost are determined for truck and trailer types that have been selected by the user to deliver woody material of single or multiple types to single or multiple origin (sawmill) and destination (plants or harbor) points in each daily trip.

Data collection

Data used to build BIOTRANS came from two main sources: a western Oregon trucking company and the Oregon Department of Transportation (ODOT). Basic costing information related to chip van trucks and used to calculate fixed and variable transport costs was collected from Terrain Tamers, a trucking company, located in Dillard, Oregon, which handles over 20,000 loads of woody biomass per year. The input data used in the calculation of transportation cost are shown in Table 1. It should be noted, however, that the costing portion of BIOTRANS was developed independently of Terrain Tamers and may or may not reflect their actual costs.

Terrain Tamers also provided much of the travel time data. 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. 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 3,893 trips. From these data, we identified 45 sawmills 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. These were located near the Interstate 5 freeway and on the Oregon Coast in western Oregon. Transported materials were hog fuel, sawdust, shavings, and chips produced from the processing of mixed softwoods in sawmills. While most of the hog fuel, shavings, and sawdust were hauled to energy plants, clean chips were transported to the ocean terminals for export to Japan or to pulp mills. Of the total trips, 69 percent were for the transportation of chips, while hog fuel, shavings, and sawdust comprised 19, 14, and 5 percent of the trips, respectively. The company used two different types of trucks (three and four-axle trucks) and three different types of trailers (53-ft single trailers and 32-32-ft and 40-20-ft double trailers) during the study period. A total of six different truck–trailer combinations were identified for this model.

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 trucks for each road in Oregon. Based on this route map and travel information provided by Terrain Tamers, 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 Han (2011). 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 Han (2011). 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

Table 1.—Input cost information for different truck and trailer configurations modeled in BIOTRANS.

	Three-axle truck			Four-axle		
	Single trailer (53 ft)	Double trailer (32-32 ft)	Double trailer (40-20 ft)	Single trailer (53 ft)	Double trailer (32-32 ft)	Double trailer (40-20 ft)
Purchase price ($)						
Truck	115,000	115,000	115,000	120,000	120,000	120,000
Trailer	70,000	80,000	80,000	70,000	80,000	80,000
Machine life (mi)						
Truck	750,000	750,000	750,000	750,000	750,000	750,000
Trailer	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
Salvage value (% of purchase price)						
Truck	35	35	35	35	35	35
Trailer	25	25	25	25	25	25
Interest rate (%)	8.5	8.5	8.5	8.5	8.5	8.5
Fuel cost ($/gal)	3	3	3	3	3	3
Fuel consumption						
Fuel (mi/gal)	4.4	4.4	4.4	4.4	4.4	4.4
Oil and lube (% of fuel costs)	10	10	10	10	10	10
Road user charges						
Truck and trailer ($/1,000 mi)	100	100	100	100	100	100
Annual registration ($)	1,200	1,200	1,200	1,200	1,200	1,200
Truck and trailer maintenance ($/mi)	0.17	0.20	0.20	0.17	0.20	0.20
Insurance ($/mi)	0.06	0.06	0.06	0.06	0.06	0.06
Tire cost ($/tire)						
New truck tire cost	250	250	250	250	250	250
Retread truck tire cost	170	170	170	170	170	170
New trailer tire cost	350	350	1,100	350	350	1,100
Retread trailer tire cost	260	260	733	260	260	733
Tire life (mi/tire)						
New front axle tire	40,000	40,000	40,000	40,000	40,000	40,000
New drive axle tire	50,000	50,000	50,000	50,000	50,000	50,000
New trailer tire	45,000	45,000	45,000	45,000	45,000	45,000
Retread drive tire	40,000	40,000	40,000	40,000	40,000	40,000
Retread trailer tire	36,000	36,000	36,000	36,000	36,000	36,000
No. of front axle tires	2	2	2	2	2	2
No. of drive axle tires	8	8	8	10	10	10
No. of trailer tires	16	20	8	16	20	8
Percentage of new drive tires	20	20	20	20	20	20
Percentage of new trailer tires	20	20	20	20	20	20
Distance on retread compared with new tire (%)	80	80	80	80	80	80

loaded travel time because the model was developed based only on loaded trip data. Generally, empty travel time is shorter than loaded travel time because of the decrease of travel resistance associated with the lower 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 percent lower for loaded travel than for unloaded travel in Oregon. Additionally, Terrain Tamers' 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 with 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 based on prediction models described in Han (2011). Loading and unloading time estimates were based on the type of material transported and the trailer types.

Model development

BIOTRANS allows the user to specify a truck configuration, a haul route, the number of loads, and the type of material transported, and then the model analyzes the production and costs of the specified transportation system. Profit and risk allowances were not included in the cost estimates produced by BIOTRANS. The model was constructed with six linked worksheets. All of the worksheets include default data for a simulated western Oregon transport company but also allow the user to input their own data (route characteristics, payloads, and times) 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).

Total trucking production and costs for a particular transport situation are determined by selecting a truck and trailer configuration (six choices), an origin (45 choices), a destination (20 choices), and transported material type (four choices) for each of up to six trips for the day of interest. In the output part of the model, trucking production (green ton [GT] miles per year) and cost (dollars per year and dollars per GT mile) are provided.

The second worksheet is the travel route information page, which is linked with the summary page. This page includes route characteristics, estimated travel time, estimated loading and unloading times, and the payload for each trip, truck configuration, and transported material type selected by the user.

The third worksheet includes loading and unloading times and payloads for each truck and trailer configuration. A total of six different truck and trailer combinations are used in BIOTRANS (Table 1). The maximum payload is dependent on the truck and trailer configuration and the transported material types.

The fourth worksheet contains labor cost information. The information related to labor cost was collected from an interview with a trucking supervisor. The basic wage for a truck driver is $14 per working hour, and the maximum working hours are set at 10 hours in 1 day.

The fifth worksheet shows overhead cost information. Overhead costs in this model include office rental, supervision, clerical, office equipment, postage and phone, and public liability costs.

The sixth worksheet calculates the fixed and variable cost information for each truck and trailer configuration (Fig. 1). Default input values used on this page are presented in Table 1.

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 three-axle truck with single trailer (53 ft). 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/h, fuel price at $3.00/gal, an interest rate of 11 percent, maintenance and repair costs of $0.17/mi, and tire costs of $0.16/mi.

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

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 1.—Truck and trailer cost page of BIOTRANS.

of a 10 percent change in labor or maintenance and repair costs on transportation cost.

Results and Discussion

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 2 provides the distribution of component costs, as modeled in BIOTRANS, based on the average transportation circumstances in western Oregon as reported by Terrain Tamers.

Labor (27%) and fuel (28%) costs are the two largest components of total cost for recovered wood waste and chip transport. Similar results have been reported for log transport modeling in Canada and the western United States (Blair 1999, Murphy and Wimer 2007). 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 percent of cost is made up of road user charges (4%), oil and lubricants (3%), insurance (2%), and registration (1%).

Effects of truck configurations

The effect of six different truck and trailer combinations were examined while holding overhead costs constant (Table 2). Different configurations directly affect fixed and variable equipment costs as well as labor costs.

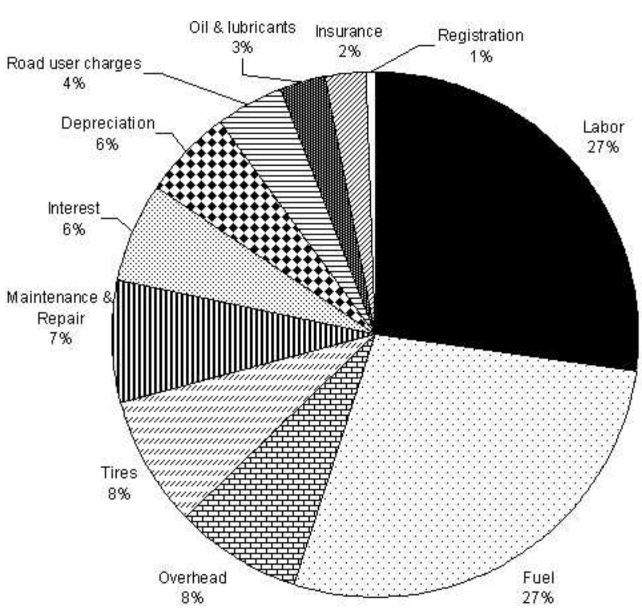

Figure 2.—Truck operating cost components.

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 four-axle truck and double trailer results in higher depreciation and interest costs compared with a three-axle truck and single trailer.

For variable costs, different truck and trailer configurations 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 three-axle truck with single trailer produced the lowest total truck cost, while a four-axle truck with double trailer (40-20 ft) had the highest total truck cost.

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 2). In BIOTRANS, single trailer configurations had lower labor costs than double trailer configurations.

Truck productivity (GT miles per year) was different with truck and trailer configurations when travel distance was constant. In BIOTRANS, a four-axle truck with single trailer allowed the transport of more volume than a three-axle truck, while there was no difference in productivity between three- and four-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 2).

In BIOTRANS, a four-axle truck with single trailer was the most cost-efficient truck and trailer type when trucking rate (dollars per GT mile) is used as the basis for comparisons (Table 2). Although the four-axle truck with single trailer has higher operating costs than a three-axle truck, its higher productivity compensates for the higher operating costs and consequently produces a lower trucking rate than found for a three-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 three-axle truck has a lower trucking rate than a four-axle truck. This result was due to operating cost alone because productivities between three- and four-axle trucks are constant. Double trailers were more cost-effective than a single trailer on a three-axle truck but less cost-effective on a four-axle truck.

Effects of transported materials

Recovered wood waste comes in a wide variety of forms, from hog fuel to sawdust. These materials have very different properties for loading and unloading as a result of their different load densities. The load density of woody biomass can be defined by comparing the proportion of the load volume that is airspace to the proportion that is solid material. Scion (2009) found that the load densities of hog fuel and chips (35% to 45%) were slightly lower than those of sawdust (40% to 45%). However, the load density of shavings was much lower (20%) compared with 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. In addition, the different properties of the

Table 2.—Transportation costs and productivity for different truck and trailer configurations for a 100-mile (one-way) trip hauling hog fuel.[a]

Truck configurations	Labor ($/y)	Overhead ($/y)	Trucking ($/y)	Total operation cost ($/y)	Productivity (GT mi/y)	Trucking rate ($/GT)
Three-axle truck						
Single trailer (53 ft)	24,794	14,300	86,468	125,562	837,000	15.00
Double trailer (32-32 ft)	27,478	14,300	90,249	132,027	918,000	14.38
Double trailer (40-20 ft)	27,478	14,300	91,489	133,267	918,000	14.52
Four-axle truck						
Single trailer (53 ft)	24,794	14,300	87,468	126,562	891,000	14.20
Double trailer (32-32 ft)	27,478	14,300	91,249	133,027	918,000	14.49
Double trailer (40-20 ft)	27,478	14,300	92,489	134,267	918,000	14.63

[a] GT = green ton.

materials also affect loading and unloading times. For example, hog fuel has significantly shorter average loading and unloading times than other materials because of its particle size and relatively high water content (Han 2011).

The differences in payloads and loading and unloading times among types of woody biomass directly affect total trucking costs. As shown in Figure 3, shavings have about 30 percent 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 or energy content (e.g., dollars per megajoule [MJ]). This may compensate for the high trucking cost. In other materials, hog fuel has the lowest trucking costs compared with chips and sawdust, but these differences are not statistically significant at the $P = 0.05$ level.

Effects of travel distance and route

Travel distance has a 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 routes were generated by different compositions of road class. The routes were defined as follows:

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

Basic.—Twenty-five percent freeway, 25 percent highway road having good grades and few bends, 25 percent highway having adverse grades and many tight curves, and 25 percent urban road.

Best.—Fifty percent freeway, 40 percent highway road having good grades and few bends, 5 percent highway having adverse grades and many tight curves, and 5 percent urban road.

The test was examined for a three-axle truck with a single trailer for a range of transportation distances between mills and delivery points. The number of loads carried per day was limited by a daily maximum of 11 working hours. As expected, transportation costs (dollars per GT) increased with increasing travel distance (Fig. 4). Similar results were reported by Grebner et al. (2005) for log products transported in the southern United States.

Road standards were shown to affect transportation costs. As shown in Figure 4, the worst routes had higher transportation costs 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 costs. In contrast, lower transportation costs were associated with the best route

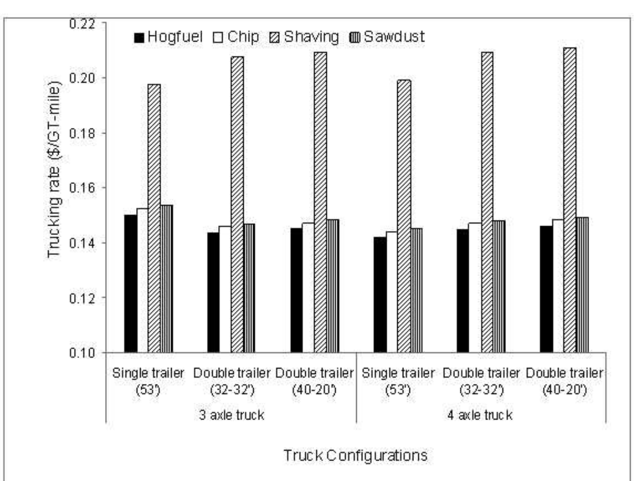

Figure 3.—Trucking costs with different types of woody biomass.

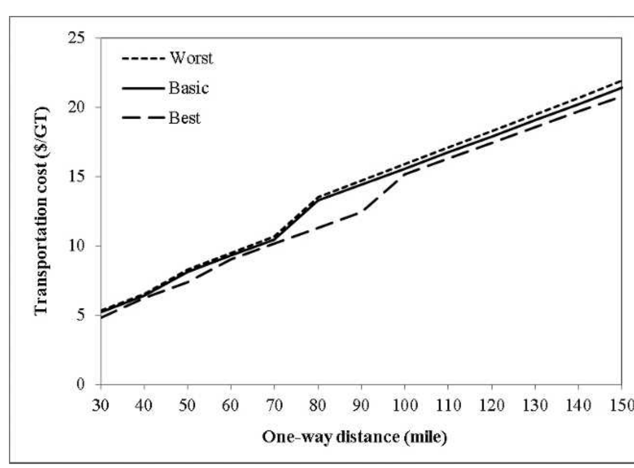

Figure 4.—The effects of travel distance and road conditions on transportation costs for a three-axle truck with a single trailer carrying chip (maximum working hours was 11 h/d).

conditions, mainly resulting from more use of freeways that had the highest travel speed. For some distances, longer travel times on the worst roads also resulted in fewer loads per day. For example, at a one-way travel distance of 80 to 90 miles, transportation costs on the worst route were up to 16 percent higher than those on the best route.

Effects of backhauling

Empty travel, particularly for longer travel distances, is often considered to be inefficient performance in transportation cost analysis. 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. Implementation of backhaul trucking is often considered to be one of the least expensive methods for improving transportation costs (Murphy 2003). However, its implementation is often limited as a result of the difficulty of finding another load near the previous unloading place. In our study, backhaul trucking was evaluated on five different routes. The average one-way distance was 166 miles, 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 use of backhaul trucking produced substantial savings on transportation costs: 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 that reported in New Zealand (Murphy 2003).

Sensitivity analyses

Fuel price directly affected total fuel cost (dollars per year) and total transportation costs (dollars per 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 5.

A 10 percent change in fuel price changes total cost by \$4,938 per year per truck (3.1%). 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 to 60 mi/h. In our study, a 10 percent increase in speed on all classes of road results in a 4 percent decrease in total transportation costs.

A fixed fuel consumption rate of 4.4 mi/gal was initially used in BIOTRANS. The effects of using different fuel consumption rates for different road classes on transportation costs are shown in Figure 6. Different fuel consumption rates for different road classes have been reported in a study by the American Transportation Research Institute (ATRI 2009). They found that fuel consumption ranged from 4.0 mi/gal for urban roads to 4.9 mi/gal for freeways. The urban road class had a considerably higher fuel consumption rate than other road classes because there was more gear changing associated with these roads. The sensitivity analyses we undertook were based on the same range in consumption rates reported by the ATRI. These spanned the fixed consumption rate reported by Terrain Tamers. A route running between the Interstate 5 freeway and the Oregon coast was selected for the sensitivity analysis. The analysis showed that the assumed fixed fuel consumption rate produced 3 percent higher fuel cost and 1 percent higher total transportation costs than using different fuel consumption rates for the selected route. However, if trucking had all been on urban roads versus freeway there would have been a possible increase in fuel consumption of up to 25 percent. This would have resulted in a maximum increase in daily costs of 6 percent.

Sensitivity analyses of labor, maintenance and repair costs, and interest are presented in Table 3.

Labor cost, along with fuel costs, is one of the two largest cost components of total transportation costs. The default

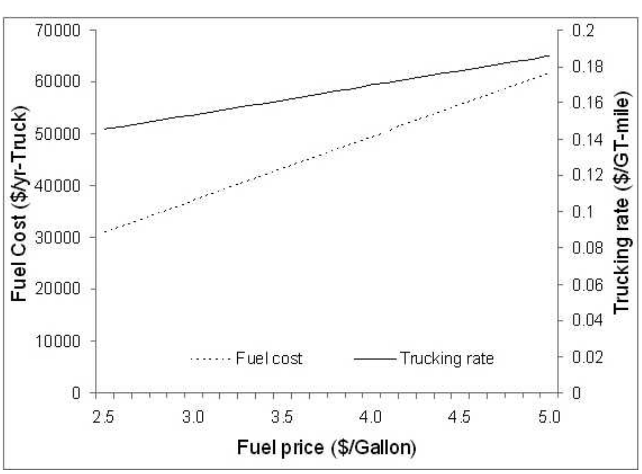

Figure 5.—The effects of fuel price on transportation costs for a three-axle truck with a single trailer carrying hog fuel.

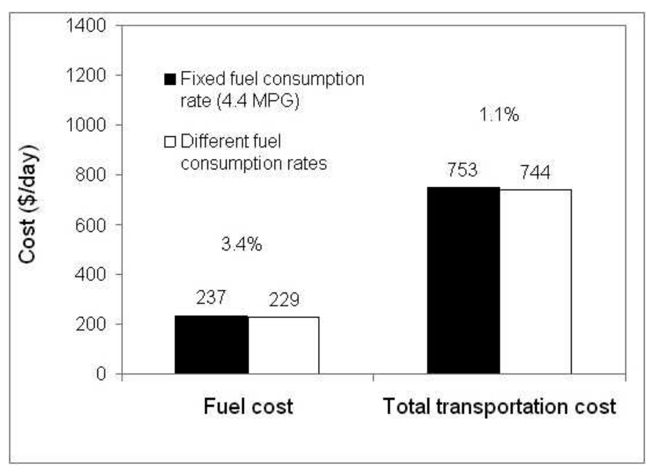

Figure 6.—The effects of different fuel consumption rates on transportation costs for a three-axle truck with a single trailer carrying hog fuel.

Table 3.—Sensitivity analysis for labor, maintenance and repair, and interest rate on total transportation costs.

Variable	10% increase from base case	% increase or decrease in total transportation costs
Labor (\$/h)	1.40	+3
Maintenance and repair (\$/mi)	0.02	+1.5
Interest rate (%)	1	+0.5

labor rate in BIOTRANS is $14/h. 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 use. Generally, new equipment has lower maintenance and repair costs, 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 costs 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.

Conclusions

In this study, a trucking production and costing model was developed to estimate transportation productivity and cost when hauling recovered wood waste from mills to energy conversion and export facilities in western Oregon. Novel aspects of this model include that the productivity component of it was based on a very large, real-world data set and it allowed determination of costs for multitrip/multicommodity transport by a range of truck configurations.

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 four-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 three-axle trucks than with four-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 costs. However, its implementation is often limited because of 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 the 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 used to plan and optimize the woody biomass transportation by allowing the user to vary truck configurations, travel routes, and other transportation cost parameters (Han 2011). This improved knowledge for woody biomass transportation will hopefully lead to increased transportation efficiency in the trucking industry and improve the use of woody biomass for energy production.

Further development of the model is warranted to improve the logistics of woody biomass transportation. By linking the moisture content to the type of material to be delivered to energy conversion plants, the energy value could be calculated and costs specified in a dollars per MJ mile as well as a dollars per GT mile basis. This may require research on the moisture content of recovered wood waste coming from different wood species and different types of processing facilities in Oregon. Other cost measures should also be addressed, for example, the carbon footprint from delivering the material, environmental impacts, and traffic safety by using particular routes. Addressing these costs may result in the selection of different routes for delivery than those based on simple costs alone.

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