FEEDSTOCK LOGISTICS (PART 6 OF 6)

TASK 5: DEMONSTRATE AND EVALUATE NEW TRAILER DESIGNS TO IMPROVE TRANSPORT EFFICIENCY

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1. Introduction

A major challenge for transporting forest residues is access to the forest with large trailers, particularly in steep terrain. The goal of Task 5 is to describe the parameters affecting large trailer access and then describe opportunities to improve large trailer access. Section 2 describes parameters affecting large trailer access to forest residues in steep terrain. Section 3 describes a case study evaluating the use of self-steer trailers and a decision-making framework. Section 4 evaluates the use of double trailers in steep terrain. Section 5 evaluates opportunities to temporarily improve critical sections of roads and introduces a decision support system to identify the optimal choice of trailer and road improvement investment. This document draws heavily from published peer reviewed manuscripts developed by investigators in the NARA project. In particular, we recognize:

Section 2.
Sessions, J., J. Wimer, F. Costales, and M. Wing. 2010. Engineering considerations in road assessment for biomass operations in steep terrain. **West. J. Appl. Forestry 25(5), 144–154**.

Section 3.
Daugherty, B. 2017. Improving large trailer access for biomass recovery in steep terrain. Master of Forestry project paper. Oregon State University. 26 p.

Section 4.
Zamora, R. and J. Sessions. 2015. Are double trailers cost effective for transporting forest biomass on steep terrain**? California Agriculture Journal 69(3), 76-81**. doi: 10.3733/ca.v069n03p177.

Section 5.
Beck, S. and J. Sessions. 2013. Forest road access decisions for woods chip trailers using Ant Colony Optimization and breakeven analysis. **Croatian J. of Forest Engineering 34(2), 201-215.**

2. Chip Trucks and Chip Vans

Conventional delivery systems include chipping or grinding of harvest residues (comminution) at the landing or a satellite yard in the forest and transporting the material with chip trucks to a power facility. Most of the forest transportation system has been designed and built for long log, stinger-steered trailers without concern for chip van access. The primary challenges for chip van access include horizontal and vertical geometry, road cross-section and turnarounds (Sessions et al., 2010). Truck and trailer configurations include 40 to 53-ft, 5th wheel chip trailers with fixed location tandem axles (Table FL-5.1), sliding tandem axles (such as shown in Figures FL-5.1 through FL-5.7), stinger-steered chip trailers (Figure FL-5.2), rear-axle steered chip trailers (such as Figure FL-5.8), and straight-bed trucks used to deliver drop boxes. The truck tractors are long-nose cabs with wheel bases of 180 to 240 inches and cramp angles of 36 to 50 degrees. Truck tractors for off highway use normally have mechanical suspensions for better traction, as opposed to airbag suspensions on paved highways. Other configurations, such as doubles and B-trains, are not commonly used in steep terrain.

Table FL-5.1. Dimensions and capacities of some observed 5th wheel and stinger-steered chip vans. Notes: 1: one unit = 200 cubic feet, 2: range of sliding trailer axles.

Type	Design	Trailer Length (ft)	Capacity (Units[1])	L1 (ft)	L2 (ft)	L3 (ft)
Stinger	Rectangle	42	13	19-20	9-10	20-22
5th Wheel	Rectangle	44	14	19-20	2-3	30-35[2]
5th Wheel	Drop Center	45	17	19-20	2-3	32
5th Wheel	Rectangle	48	18	19-20	2-3	37-38
Stinger	Rectangle	48	19	22	10-11	22-23

Figure FL-5.1. Truck Tractor with 5th wheel chip van on a horizontal curve. Reed's Fuel & Trucking operating near Dillard, OR.

2.1. Road Width and Off-tracking

Because the rear wheels of most tractor-trailer combinations cannot track directly behind the truck tractor drive wheels (Figure FL-5.1), the road must be sufficiently wide to permit passage of the truck tractor and trailer. The vehicle configuration, central angle of the curve, and length of the curve determine the minimum road width. The minimum lane width can be estimated using the following equation when R>L.

$$MLW = 10 + \left(R - \sqrt{R^2 - L^2}\right)\left[1 - \exp\left(-0.015\Delta\frac{R}{L} + 0.216\right)\right] \qquad [1]$$

Where R is the centerline radius, ft, L is the wheelbase factor, ft, Δ is the central angle in degrees, and $L = \sqrt{L_1^2 \square L_2^2 + L_3^2}$ (BLM, 1984). For L_1, L_2, L_3 definitions, see Figure FL-5.2 for 5th wheel chip vans and Figure FL-5.3 for stinger-steered trailers. Plotting lane width as a function of curve angle and radius shows the difference for the two types of trailers (Figures FL-5.2, FL-5.5) for radii greater than 50 ft. However, in tight situations, we have observed curve radii less than 50 ft being successfully negotiated. We observed a 20-ft wheelbase tractor pulling 33-35 ft wheelbase vans around a 28-ft centerline radius, central angle approximately 120 degrees, with a 31-ft lane traveled way (outside steering wheel to inside trailer wheel). With the 35-ft trailer wheelbase, L= 40.3, the vehicle is almost identical to the example vehicle for Figure FL-5.5. Although the lower range of radii in Figure FL-5.5 is 50 ft, you can see that a 31 ft traveled way with a 28 ft radius field observation is a reasonable projection on the graph at a central angle of 120 degrees. More complicated horizontal geometry such as compound curves and reverse curves can be evaluated using software such as Erkert and Sessions (1989) and add-ons for commercial CAD programs.

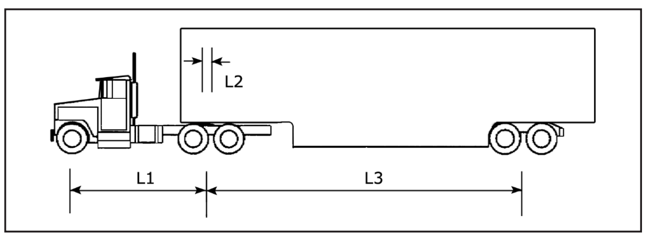

Figure FL-5.2. Wheelbase definitions for a 5th wheel chip van. L1 is wheelbase of the truck tractor, L2 is the offset of the king pin in front of the midpoint of the drive axles and L3 is the distance from the middle of the drive axles to the midpoint of the trailer axles.

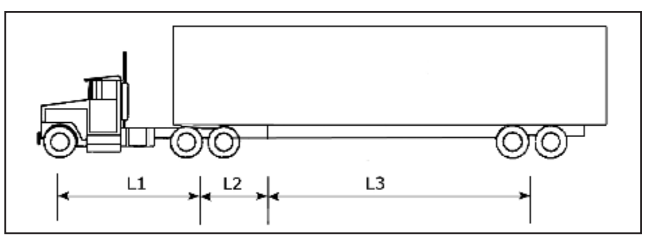

Figure FL-5.3. Wheelbase definitions for a stinger-steered chip trailer. L1 is the wheelbase of the truck tractor, L2 is the length of the stinger, and L3 is the length of the reach.

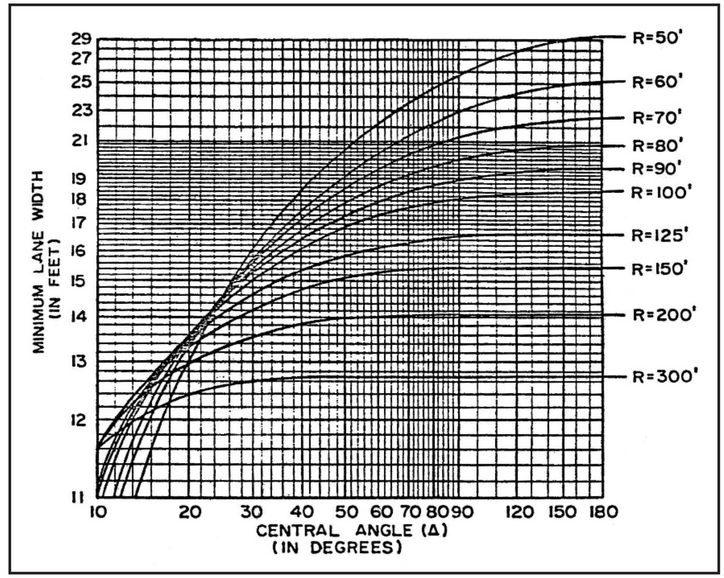

Figure FL-5.4. Minimum lane width as a function of central angle and centerline curve radius for a 5th wheel chip van with an 18-ft tractor and a 36-ft trailer with zero 5th wheel offset (L=40.25 ft). From BLM Manual, H-9113-1 Roads, Release 9-218, May 14, 1984.

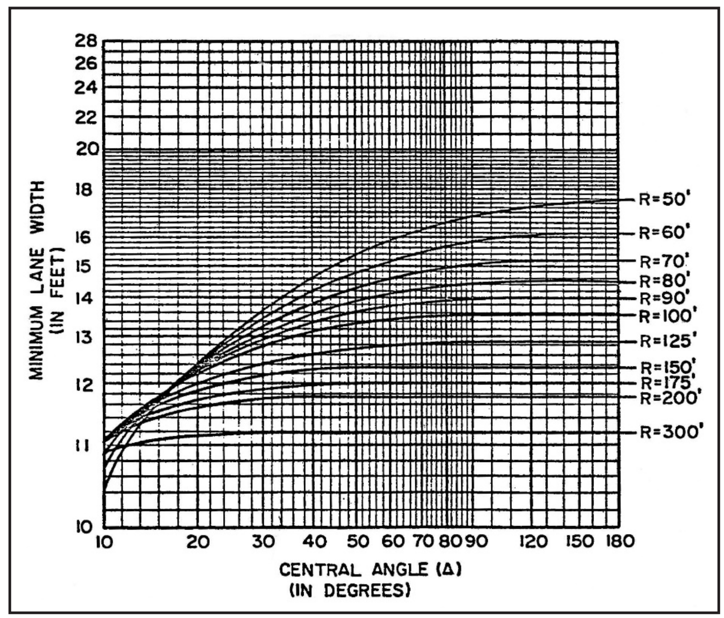

Figure FL-5.5. Minimum lane width as a function of central angle and centerline curve radius or a truck tractor with stinger-steered trailer. Truck tractor is 20-ft tractor, with a 10-ft stinger, and "bunk to bunk" distance of 30-ft (L=26.46 ft). From BLM Manual, H-9113-1 Roads, Release 9-218, May 14, 1984.

Chip vans vary in dimensions and capacity (Table FL-5.1). The conventional 5th wheel chip van requires a wider lane width than a stinger-steered chip van. Stinger-steered chip vans are now manufactured by several trailer manufacturers (Figure FL-5.6). The box sits slightly higher than the conventional chip van and a drop center (possum belly) is not available. Tracking of the stinger-steered chip van is similar to a pole-length log truck of equal dimensions. Sliding trailer axles are available from several trailer manufacturers which allow shortening of the trailer wheelbase by 5 to 8 feet. This reduces off-tracking and increases maneuverability for the loaded and unloaded chip van. However, the axles must usually be lengthened upon re-entry to the public road system to meet legal specifications for carrying capacity. Western Trailers has recently developed a prototype 5th wheel, rear steerable axle chip van for Hermann Bros, Port Angeles, WA (Figure FL-5.7) that has negligible off-tracking (Burt, 2010).

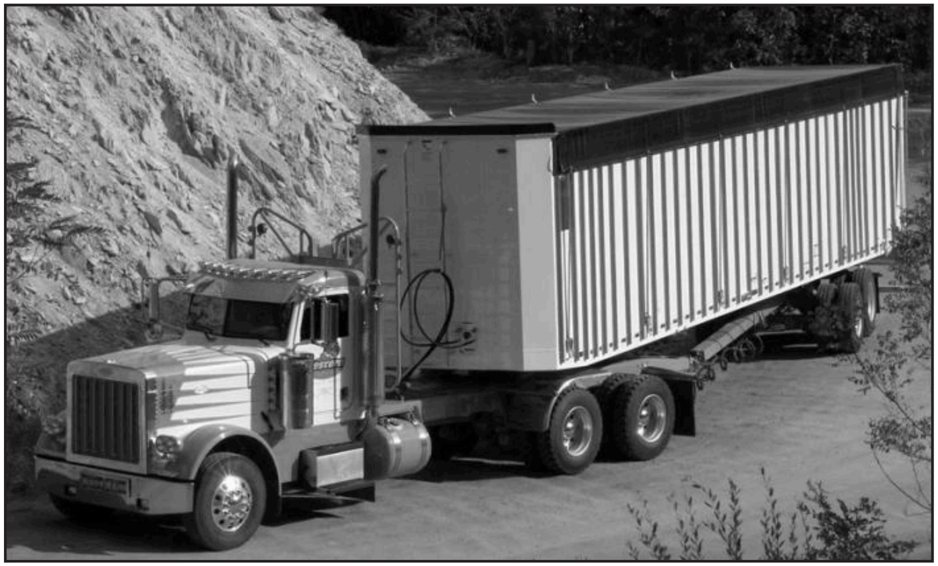

Figure FL-5.6. Stinger-steered chip van. Western Trailers, near Boise, Idaho.

Figure FL-5.7. All-wheel drive truck tractor with 5th wheel chip van with steerable rear axles. (Hermann Brothers, Port Angeles, WA).

2.2. Gradeability

Gradeability depends primarily on the weight on the driving axles, gross weight of the vehicle, and the coefficient of traction. On tangents, where either wheel loading is not equal or if traction conditions are not uniform, the ability to lock the inter-axle and individual axle differential gears can be decisive (Figure FL-5.8). All other things being equal, individual axle locks, known as “lockers” plus the inter-differential lock provide the greatest ability to utilize the available traction.

The truck suspension system affects gradeability. Truck tractors on logging roads often have mechanical suspensions as compared to on-highway truck tractors that have airbag suspensions. From our observations, conventional airbag suspensions can reduce maximum gradeability for the unloaded vehicle, perhaps 2% or more, because they cannot maintain road contact over uneven surfaces as well as some mechanical suspensions. To counter this tendency to bounce, some operators adjust the air pressure to one of the driving axles for the unloaded vehicle so that one driving axle is carrying most or all of the load on the drivers. This keeps the more heavily loaded axle in better ground contact. The pressure is then returned to normal before the vehicle is loaded. Some mechanical suspensions have after-market airbags added to them to restrict walking beam motion in uneven terrain.

Figure FL-5.8. Truck tractor with unloaded chip van on 15% adverse grade. Sliding trailer axles in forward position. Reed's Fuel & Trucking operating near Dillard, OR.

Gradeability of unloaded chip vans is a concern on steep roads (Figure FL-5.8). Unloaded chip vans have a much lower proportion of their total weight on the driving axles compared to log truck tractors that carry pole trailers piggyback. A typical end-dump chip trailer weighs 11,000 lb to 15,000 lb with weight on the kingpin in the range of 3000-4000 lb. Live floor chip vans (unloading by moving floor as opposed to gravity) add an additional 3000 to 3500 lb to the trailer with a kingpin load of 4000-6000 lb. Stinger-steered trailers with live floors weigh 15,000 to 17,000 lb with 4,000-6,000 lb on the kingpin. Truck tractors weigh about 17,000 lb to 19,000 lb with 45-50 percent of the weight on the rear axles.

The steepest grade a truck tractor with chip van can climb either in forward or backing motion at a constant velocity is approximately:

$$\% \text{ Grade} = 100\, x\, [\, u\, x\, (WD/W) - RR] \qquad [2]$$

Where u = coefficient of traction, RR = coefficient of rolling resistance, WD is the weight on the driving axles and W is the gross vehicle weight of the unloaded chip van. On gravel roads, RR can be approximated as 0.02 lb/lb (Byrne et al., 1960). Thus, for a 32,000 lb tractor trailer with 14,000 lb on the driving axles, the steepest grade for a coefficient of traction =0.4 is:

$$\% \text{ Grade} = 100\, x\, [0.4 \text{ x } 14{,}000/32{,}000 - 0.02)] = 15.5\% \qquad [3]$$

More accurate formulas that account for weight transfer between axles are presented in Sessions et al. (1986) and Chung and Sessions (2004). Gradeability of doubles, both unloaded and loaded is lower than that of single trailers. The kingpin is usually placed 2-3 feet in front of the midpoint of the tractor drivers to distribute the load between the front axle and drive axles optimally for loaded on-highway transport. Depending upon the moisture content of the chips/grindings, the truck and trailer may be volume limited rather than weight limited. If the load is volume limited, the 5th wheel may not need to be positioned as far forward. Traction for the unloaded chip van could be increased slightly by moving the 5th wheel directly over the drivers. Sliding 5th wheels are available but add weight to the tractor.

When starting from a dead stop, the force due to acceleration increases the traction requirements. Much depends on the skill of the driver, but as a rule of thumb, the additional force to accelerate the vehicle from a stop using a mechanical transmission is equivalent to a 6-10 percent grade, in addition to the actual grade. This is equivalent to a startup acceleration for the empty vehicle of about 3 ft/sec^2, well within the mechanical startup capability of many heavy vehicles. Thus a truck with mechanical transmission starting on a 6 percent grade, depending on driver ability, may need to have traction capability equivalent to successfully climbing a 12-16 percent grade at constant speed. Automatic transmissions have greater control during startup and will have less impact.

The coefficient of traction depends upon surface type, degree of compaction, road smoothness (raveling, wash boards), moisture, and tire inflation. Road conditions degrade with traffic so the coefficient of traction needs to be monitored. For radial tires, reduced tire inflation increases the coefficient of traction (Fitch, 1994). The amount of increase depends upon the increase in length of the footprint as the tire pressure is reduced. Central tire inflation systems are available to permit tire pressure adjustment from the cab. In shuttle truck applications, pressures on the drive tires can be lowered for the duration of the job since the trucks are running at low speeds.

In a pinch, an assist vehicle can pull the empty chip van across a rough spot. For example, a four-wheel drive, 6000 lb pickup truck on a compacted gravel surface (coefficient of traction =0.4) has about 1200 lb of surplus pull on an 18% grade that could be used to assist a chip van (6000 x 0.4 - 0.18 x 6000 - 0.02 x 6000). A 32,000 lb chip van with 14,000 lb on the drivers requires about 6400 lb of pull (0.18 x 32,000 + 0.02 x 32,000) to overcome grade resistance and rolling resistance but can develop only about 5600 lb of pull (14,000 x 0.4) at u=0.40 due to the limited traction. For these conditions, a pickup assist would be sufficient. Sandbags or other added weight in the pickup or the use of heavier auxiliary vehicles provide greater assistance. Otherwise, without assistance, the unloaded chip van would be limited to about 15.5% grade (u=0.40).

All wheel drive can boost gradeability by increasing the proportion of weight on the drive axles (Figure FL-5.8). For the previous case, the addition of all wheel drive would allow the unloaded chip van to successfully climb grades in excess of 20% grade if the rear-wheel only vehicle was limited to 15-16%. In some cases, an all-wheel drive shuttle truck could be used to swing trailers up steep grades.

For short steep adverse grades, which exceed the tractive ability of the truck, the momentum of the vehicle can be used. “Momentum” grades depend primarily upon the speed of the chip van entering the grade, the length of the grade, and the pull that can be maintained through the grade.

The steepest grade that a truck can climb on a momentum grade can be estimated as:

$$\% \text{ Grade} = 100 * [0.5 \times (W/32.2) \times (V_1^2 - V_2^2) + T \times S - RR \times W \times S] / (W \times S) \qquad [4]$$

Where W is the gross vehicle weight, V_1 is initial velocity entering the momentum grade, V_2 is the ending velocity at the top of the grade, RR is the coefficient of rolling resistance, and S is the length of the grade. For example, if the 32,000 tractor trailer is entering a 200 ft long grade at 15 ft/sec (10 mph) and exiting the grade at 7 ft/sec (4.7 mph) with a coefficient of rolling resistance = 0.02 while being able to maintain a thrust of 5600 lb on the grade, the maximum grade is

$$\% \text{ Grade} = \frac{100\ [.5 \times 32{,}000/32.2 \times (15^2 - 7^2) + 5600 \times 200 - .02 \times 32{,}000 \times 200]}{(32{,}000 \times 200)} = 16.9\% \qquad [5]$$

We have observed successful passage of empty chip vans on gravel roads on momentum grades with short pitches up to 22% with entering speeds of 20 mph.

Gradeability on curves is lower than gradeability on tangents due to a number of factors. These factors include additional cornering forces of the steering wheels, tandem axle drag, and unequal loading of the drive axles due to a combination of centrifugal force, superelevation, the angle of pull of the trailer on the truck tractor, and the need to keep individual axle differentials unlocked. For road design, the USDA Forest Service (1987) recommends reducing the grade on switchbacks by .04% per degree of curve. Therefore, if the maximum gradeability of an unloaded chip van on a tangent is 15.5% and the curve radius is 70 feet, the chip van will probably have difficulty on grades greater than 12.5% (15.5-3.0) without relying on truck momentum.

Although unloaded chip vans on adverse grades are the most common gradeability concern, pulling loaded chip vans up adverse grades can be a limiting factor. Maximum gradeability for the loaded chip van is created when the tractor drop axle is in the up position so that maximum loading of the drivers is achieved. Drop axles must usually be lowered for travel on public roads to meet legal highway loadings.

2.3. Turn Around

Perhaps the largest challenge with chip vans is turning the vehicle around at the landing. The options include: (1) backing into a road intersection to turn around and then either backing up to the landing or driving forward to the landing, (2) turning at a wide space such as a ridgetop landing and then either backing up to the landing or driving forward to the landing, (3) creating a stub turnaround on the nose of a ridge. Factors affecting the ability of the truck to turn around include the wheelbase of the truck tractor, the maximum cramp angle of the inside steering wheel, and the wheelbase of the trailer. Terry and Shuster (1996) investigated the path of a reversing tractor-trailer backing into a loading dock. For a 22.3 ft tractor pulling a 48 ft trailer with a trailer wheelbase of 29.9 ft, (king-pin to middle of trailer axles), their field measurements indicated that the tractor-trailer required about 40 ft by 80 ft (3200 ft^2) to maneuver.

Backing is time consuming and hard work for the driver with a travel speed of 0.5 to 1 mph. Gradeability for backing on to landings, road intersections or other situations is an important consideration. Opportunities to increase gradeability with the use of assist vehicles or momentum grades are limited. If the empty chip van needs to start backing from a dead stop, additional traction is needed to overcome acceleration forces adding 6-10% to the effective grade. Access to landings should be verified during the road assessment.

Backing into an intersection depends upon the skill of the driver and geometrics of the intersection. Backing into an intersection is easiest if the intersecting road is at the same elevation or upsloping and if the driver is backing up on a clear side turn, i.e., the driver should be looking the driver side rear-view mirror. If the throat on intersecting road is 70 ft wide with a 60 ft transition, the truck should be able back in and drive out. Ditches and pipes may need to be protected. Putting plywood over the pipe ends to prevent plugging and filling the ditches with chips has been used.

Measurement of several 20-ft wheelbase tractors with 31-35 ft king-pin to middle of trailer tandem axles indicated that the truck and trailer could enter and turn in a 63 to 70 ft diameter circle (3120 to 3850 ft^2) with a little maneuvering. Additional maneuvering (multi-point turns) can reduce this area significantly. In a multi-point turn, the truck maneuvers the trailer into a jackknife position and then pivots around the trailer axle(s) with the radius of the tractor turn being controlled by the length of the tractor wheel base and the maximum cramp angle for the inside steering wheel. For multi-point turning, the width of the turnaround for the 5th wheel trailer can be estimated as the wheelbase of the trailer plus one-half the width of the truck tractor (4 ft) plus an allowance for maneuvering. For example, for a 35-ft wheel base trailer, allowing 8 ft for maneuvering = 35 + 4 + 8 = 47 ft. A reasonable maneuvering length is equal to the overall wheelbase of the vehicle plus 15 ft. If the truck and tractor overall wheelbase is 55 ft, then a rectangle 47 by 70 feet should be adequate, although the actual maneuvering area is more of a tear-drop shape.

During the multi-point maneuver, the 5th wheel trailer may jackknife to 90 degrees or more (Figure FL-5.9). This can easily be accomplished with a 5th wheel trailer, but the jackknifing ability of a stinger-steered chip vans is limited to the length of the extension of the reach (Figure FL-5.2). Longer extensions can be installed, but longer extensions increase the possibility of binding the extension during a turn and possibly bending it.

Figure FL-5.9. Turning on a landing. Reed's Fuel & Trucking, Mt. Salem, Oregon.

2.4. Vertical Curves

Both crest and sag vertical curves could affect chip van passage. Crest vertical curves are the more limiting. Drop center chip vans may have only 8-12 inches of vertical clearance on level ground. Clearance over crest vertical curves is usually only a problem when entering or leaving a spur road at its junction with the main road. Since lowboys have 8-12 inches of clearance, one rule is that if a lowboy can successfully cross the intersection, a drop center chip van can probably cross as well. With sag vertical curves, the concern is the front end of the trailer hitting the frame of the truck tractor. If the vertical curve data and dimensions of the vehicle are known, the clearance can be calculated in the office.

3. Evaluation of All-wheel Drive Truck with Rear-steer Trailer

Hermann Brothers Logging contracted with Western Trailers (Boise, Idaho) to develop hydraulic rear-steer (force-steer) trailer to use with their 6x6 logging truck tractors. The trailer is 48-ft long with a drop center. Trailer steering is controlled by the operator with a hand-operated joystick. The vertical clearance of the trailer can also be adjusted using inflatable airbags. In May, 2016 we contracted with Bill Hermann to put the truck and trailer (Figure FL-5.10) through a number of tests to confirm the vehicles mobility. As discussed earlier; off-tracking, gradeability of the unloaded trailer, and available turn-arounds often limit large trailer access requiring movement of residues to an accessible location using bin trucks or dump trucks. Description of the physical tests and an economic decision model for determining when to use the 6x6 truck with rear-steer trailer are in development by Bryent Daugherty, graduate student on the NARA project. Here are notes to illustrate the trailer mobility while the project report is being completed.

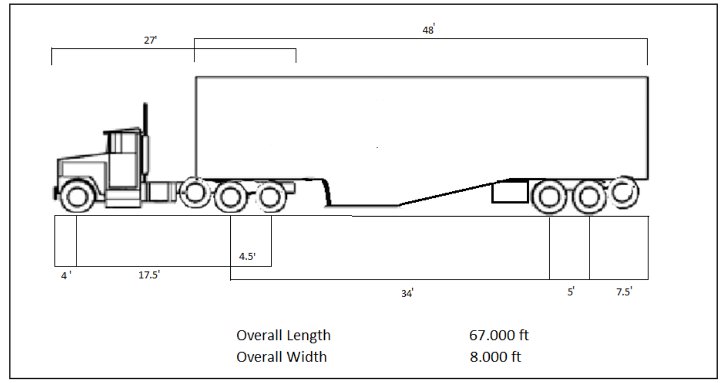

Figure FL-5.10. Dimensions of tested 6x6 truck with 48-ft trailer.

3.1. Turn Around

A rear-steer trailer used with an all-wheel drive truck has the ability to successfully maneuver turnarounds more challenging than a conventional chip trailer can operate in. These challenges include road gradient, available surface area to maneuver, angle of road intersection, and the time it takes to turn around the trailer. Under certain conditions the rear-steer trailer can use additional surface area off the road to successfully turnaround (Figure FL-5.11). Backing off road would be limited to trees less than sapling size to avoid trailer damage. The 6x6 truck compared to the 6x4 truck has the additional traction necessary to be able to drive forward into a shallow ditch allowing for more room to maneuver.

Figure FL-5.11. In a multi-part turn, the truck backed into a 47-ft deep stub, 13-ft wide with a 32-ft throat. At points during the turn, the back of the trailer was off road, as well as the truck-tractor was forward into the ditch.

As discussed in Sessions et al. (2010), if the right conditions exist, as well as in close proximity to the active job, it is possible to turn a trailer on a wide area such as a ridgetop or landing. Figure FL-5.12 shows the result of an empirical test of the minimum surface area needed to successfully maneuver a 180° multipart turn on a landing or ridgetop. For a 48 ft rear-steer trailer with a 27 ft wheelbase truck-tractor, a 53 x 80 ft rectangle was adequate to successfully turnaround. For a 48 ft conventional trailer with the same truck-tractor, a 60 x 90 ft rectangle was required.

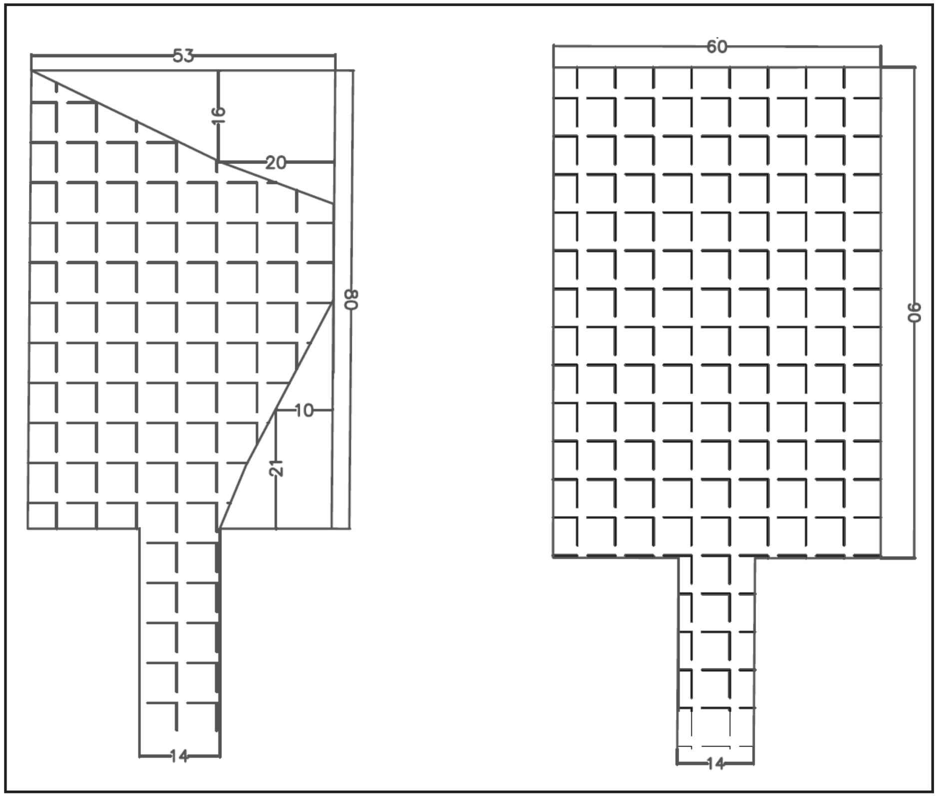

Figure FL-5.12. Rear-steer trailer vs standard chip trailer on a 180o multipart turn. The rear-steer trailer results are on the left with the standard chip trailer on the right.

3.2. Gradeability

Gradeability for the 6 x6 truck tractor with empty trailer was observed to be at least 27% (Figure F.L-5.13) on a rocked road in western Washington.

Figure FL-5.13. Climbing a 27+% grade with the unloaded trailer at Pelican Point, Olympic Peninsula.

3.3. Off-tracking

Figure FL-5.14. Negotiating a 180-degree switchback. Note direction of trailer tires.

3.4. Backing

An advantage of the rear-steer trailer allowing for increased backing speeds is that the driver is able to use the trailer to steer while backing up (Figure FL-5.15) rather than using the truck making it easier to navigate on curves reducing the time needed to correct truck position. The measured average speed, while backing up a rear-steer trailer, is around 5 miles per hour compared to the 0.5-1 mph for a conventional chip trailer mentioned in Sessions et al. (2010). However, simultaneous constraints such as steep terrain, small curve radii, weather, etc. could reduce the speed. Other challenges that could reduce the speed or preclude backing all together includes heavy wind, low visibility due to rain or fog, and reduced traction due to wet ground**.** Other advantages of the rear steer trailer when paired with an all-wheel drive truck is that it is able to drive on the side of the road over the inside ditch allowing for increased space to maneuver in tight situations. Also, using all-wheel drive trucks increases the traction on steeper terrain allowing for more areas that the truck can operate (Figure FL-5.16).

Figure FL-5.15. Backing around curve. Trailer wheels being used to guide trailer.

Figure FL-5.16. Backing unloaded up a 15% grade.

3.5. Decision Model

An economic model was developed to estimate and compare the cost of the 48-ft self-steering trailer as compared to a hook-lift truck application transporting harvest residues to a central landing near the unit. At the central landing, the residuals were piled and held until the primary transport of harvest residues from the harvest unit was completed. The residues were then processed and transported to an end facility using a 6x4 highway truck with a standard 53-foot chip van. A discrete-event simulation model was designed in Arena Simulation by Rockwell Automation to model the two transportation systems during a single 10-hour shift duration to estimate the hourly cost per dry ton for equipment that were either operating or waiting (Rockwell Automation, 2017).

Hourly machine rates were based on the standard machine rate calculation methods described in Miyata (1980) and Brinker et al. (2002). Equipment was assumed to be purchased new, and prices were provided by local contractors or determined by regional market prices for similar equipment (Table FL-5.2). For the hook-lift and chip vans, 2000 productive machine hours per year (PMH y^{-1}) were used with 1,500 PMH y^{-1} used for the Doosan DX300LL log loader and Peterson Pacific 5710D horizontal grinder. Fixed cost (Eq. 6) for the transportation and processing equipment were based on the purchase price of the machines, interest (10% of average yearly investment), insurance and taxes (5% of average yearly investment), depreciation (based on 20% salvage value and tied to expected hours of use), and machine life (5 years for grinder and 8 years for the loader and trucks).

Hourly variable cost (Eq. 6-8) included fuel cost set at \$3.00 gallon^{-1} for diesel for in-woods equipment and \$3.50 gallon^{-1} for highway vehicles. Other variable costs included lubrication calculated at 36% of total fuel cost, and repair and maintenance cost calculated at 90% of the machine depreciation. Labor cost was assumed to be \$23.61 hour^{-1} plus benefits (40% of hourly wage) and was based on the average 2015 base wage for logging equipment operators in Washington state (Bureau of Labor Statistics, 2015). Other system costs included the support equipment plus any administrative cost incurred during the operation. Profit and risk (10% of total fixed and variable cost) was added to each machine cost.

$$F_m = (D_m + I_m + T_m)/H_y \quad (5)$$
$$V_G = F_G + B_G + R_G + O_G + S_G \quad (6)$$
$$V_L = F_L + R_L + L_L \quad (7)$$
$$V_T = F_T + T_T + R_T + L_T + O_T \quad (8)$$

Where:

F_m hourly total fixed cost of machine m, ($/hr)

D_m annual depreciation cost of machine m, ($)

I_m annual interest cost of machine m, ($)

T_m annual insurance and taxes cost for grinder m, ($)

H_y annual productive machine hours (hr)

V_G hourly total variable cost of grinder, ($/hr)

F_G hourly fuel cost of grinder, ($/hr)

B_G hourly bits cost of grinder, ($/hr)

R_G hourly repair and maintenance cost of grinder, ($/hr)

O_G hourly overhead cost of grinder, ($/hr)

S_G hourly support equipment for grinder cost, ($/hr)

V_L hourly total variable cost of loader, ($/hr)

F_L hourly fuel cost of loader, ($/hr)

R_L hourly repair and maintenance cost of loader, ($/hr)

L_L hourly labor cost of loader, ($/hr)

V_T hourly total variable cost of truck, ($/hr)

F_T hourly fuel cost of truck, ($/hr)

T_T hourly tire cost of truck, ($/hr)

R_T hourly repair and maintenance cost of truck, ($/hr)

L_T hourly labor cost of truck, ($/hr)

O_T hourly overhead cost of truck, ($/hr)

To calculate the total cost for each system, the waiting cost for transportation and processing equipment were calculated based on the waiting time caused by truck-machine interaction. Total hourly waiting cost included the interest cost, insurance and taxes, overhead cost, support equipment cost, labor, and profit and risk to account for the opportunity cost lost due to the machine waiting (Eq. 9-11).

$$WTC_L = I_m + T_m + L_L + PR_L \quad (9)$$
$$WTC_G = I_m + T_m + O_G + S_G + PR_g \quad (10)$$
$$WTC_{Tm} = I_m + T_m + L_T + O_T + PR_T \quad (11)$$

Where:

WTC_L hourly waiting cost for loader, ($/hr)

WTC_G hourly waiting cost for grinder, ($/hr)

WTC_{Tm} hourly waiting cost for truck type m, ($/hr)

PR_L hourly profit and risk for loader, ($/hr)

PR_g hourly profit and risk for grinder, ($/hr)

PR_T hourly profit and risk for truck, ($/hr)

Table FL-5.2. Operating cost for equipment used in the self-steering and hook-lift applications.

	Doosan DX300LL Log Loader	Peterson Pacific Horizontal Grinder 1050 HP	Kenworth T800 Hook Lift Truck	Rear Steer-Axle 48 Ft (6x6 Truck + Trailer)	Standard 45 Ft (6x4 Truck + Trailer)	Standard 53 Ft (6x4 Truck + Trailer)
Purchase Price ($)	$ 352,000.00	$ 700,000.00	$ 150,000.00	$ 375,000.00	$ 180,000.00	$ 200,000.00
Depreciation ($)	$ 35,200.00	$ 112,000.00	$ 15,000.00	$ 37,500.00	$ 18,000.00	$ 20,000.00
Interest cost ($)	$ 22,880.00	$ 47,600.00	$ 9,750.00	$ 24,375.00	$ 11,700.00	$ 13,000.00
Insurance & Taxes ($)	$ 11,440.00	$ 23,800.00	$ 4,875.00	$ 12,187.50	$ 5,850.00	$ 6,500.00
Productve Machine Hours	1500	1500	2000	2000	2000	2000
Total Fixed cost ($/hr)	$46.35	$122.27	$14.81	$37.03	$17.78	$19.75
Bits, Grates, Anvil cost ($/hr)	-	$ 22.70	-	-		-
Tire Cost ($/hr)	-	-	$5.11	$9.53	$6.41	$9.98
Maint & Repair ($/hr)	$ 21.12	$ 67.20	$ 6.75	$ 16.88	$ 8.10	$ 9.00
Fuel & Lube cost ($/hr)	$ 23.79	$ 146.06	$ 15.71	$ 28.61	$ 25.23	$ 28.56
Overhead ($/hr)	-	$ 21.80	$ 6.70	$ 6.70	$ 6.70	$ 6.70
Support ($/hr)	-	$ 14.80	-	-	-	-
Labor ($/hr)	$ 39.66	$ 0.00	$ 36.36	$ 36.36	$ 36.36	$ 36.36
Total Variable Cost ($/hr)	$84.58	$272.56	$70.63	$98.07	$82.80	$90.60
Profit and Risk 10% ($/hr)	$ 13.09	$ 39.48	$ 8.54	$ 13.51	$ 10.06	$ 11.03
Total Cost, ($/hr)	$144.02	$434.31	$93.98	$148.61	$110.63	$121.38

Both transportation systems were compared using similar conditions, but also had varying characteristics based on the type of transportation equipment used (Figure FL-5.17). Under both scenarios, it is assumed that the harvest unit was a whole-tree cable operation with the forest harvest residues pre-piled at roadside. The material in the unit encompassed a mixture of species including Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carriere), and western redcedar (*Thuja plicata* Donn ex D. Don). The mean specific gravity used in the model was assumed to be 0.38 with a moisture content of 34% wet basis (Cross et al., 2013). Under the self-steering system, the forest harvest residues were processed in field using a grinder and a loader and then transported to a bioenergy facility. It was assumed that the equipment was transported to the active unit by lowboy at a rate of \$120 hour^{-1} and the mobilization took a total of six hours. Although the harvest residues were piled post-harvest, it was assumed that additional piling was needed before the grinding process to rearrange and move the piles closer together to allow for optimal grinder efficiency. The number of available vehicles, distance from the turnaround to the grinder, and distance to the facility was varied to evaluate sensitivity if parameters were changed, and how machine interactions affect the overall utilization of each machine.

The total cost of processing and transportation for the self-steering system, based on a dollar per bone dry ton basis (\$ BDT^{-1}), was derived from the working and waiting cost of each machine and the amount of biomass brought to the end facility (Eq. 12-17). The processing cost is dependent on the working and waiting time per shift of the loader and grinder. The processing working time is calculated based on the number of loads that enters the system multiplied by the grinding time. Each load took 28 minutes to fill a 48-ft self-steering trailer with a capacity of 28.71 green tons (GT). The processing waiting time was calculated by subtracting the working time from the total time the equipment was in the system during the shift duration. The transportation cost is dependent on the average working and waiting time of the trucks during a shift multiplied by the number of trucks in the system. The working time of a single truck is dependent on its inter-arrival time, round-trip time, and number of cycles it completed. Under the base case scenario, the average truck waiting time per shift is an accumulation of the waiting time (if any) at the turnaround and/or turnout. Because the turnaround is located before the grinder location, a truck can wait in the turnaround until the grinder is free. The

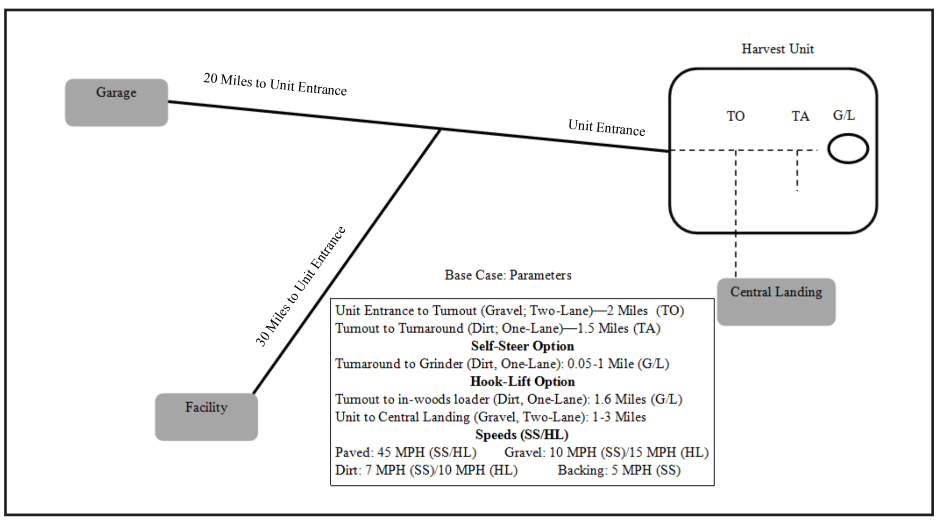

Figure FL-5.17. Base case scenario for the self-steer system and hook-lift application and parameters used in the Arena Simulation model.

truck waiting in the turnaround must remain until the truck at the grinder finishes processing and drives past the turnaround. If there are too many vehicles in the system and a truck enters the unit with both the grinder and turnaround occupied, then the truck must wait at the turnout near the entrance of the unit. The truck waiting at the turnout must then remain until the turnaround is free and allow the other truck that just finished processing drive past the turnout.

Self-Steering Trailer System Costs

$$PC = C_P + M_P \quad (12)$$
$$C_P = ((W_L + W_G) * H_{LG}) / BDTs \quad (13)$$
$$M_P = ((WTC_L + WTC_G) * Y_{LG}) / BDTs \quad (14)$$
$$TC = C_T + M_T \quad (15)$$
$$C_T = ((W_T * H_T) * N) / BDTs \quad (16)$$
$$M_T = ((WTC_{SS} * Y_T) * N) / BDTs \quad (17)$$

Where:

PC	total processing cost of self-steering system, (\$/BDT)
C_P	total processing working cost of self-steering system, (\$/BDT)
W_L	hourly working cost of loader, (\$/hr)
BDTs	bone-dry tons transported
W_G	hourly working cost of grinder, (\$/hr)
H_{LG}	working time of grinder & loader, (hr)
M_P	total processing waiting cost of self-steering system, (\$/BDT)
Y_{LG}	waiting time of grinder & loader, (hr)
TC	total transportation cost of self-steering system, (\$/BDT)
C_T	total transportation working cost of self-steering system, (\$/ BDT)
W_T	hourly working cost of self-steering truck, (\$/hr)
H_T	working time of self-steering truck, (hr)
N	Number of transportation vehicles
M_T	total transportation waiting cost of self-steering system, (\$/BDT)
WTC_{S}	hourly waiting cost of self-steering truck, (\$/hr)
Y_T	waiting time of self-steering truck, (hr)

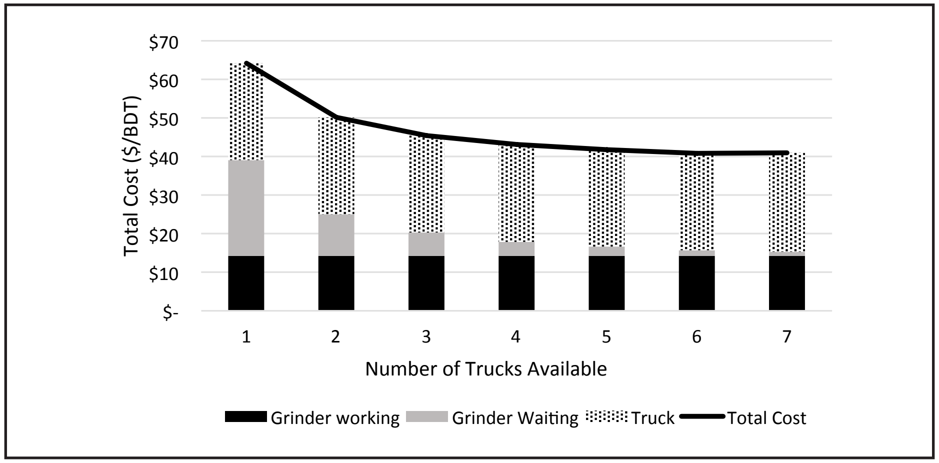

Figure FL-5.18. Total cost of the processing and transporting stages in the self-steering system with variable number of trucks available. Costs are expressed in US dollars per bone dry ton ($/BDT).

The effect of the number of available self-steering vehicles on the overall utilization for each machine type was analyzed by modeling the scenario under the base case situation and varying the number of trucks (Figure FL-5.18). Results from the operation conclude that six trucks minimized the processing and transportation cost ($40.78 BDT^{-1}) with 16 loads brought to the end facility. The maximum grinder utilization rate for six trucks was estimated to be 75% with a processing cost of $14.24 BDT^{-1}. Adding another truck to system was found to increase the grinder utilization rate by 4% but was limited by road access. Using seven trucks under this scenario increased the transportation wait time upon arrival at the harvest unit, which increased both the transportation cost and total cost ($40.88 BDT^{-1}). Total cost decreased by 36% due to an increase in the grinder utilization from 17% (one truck) to 75% (six trucks).

The distance and location of the turnaround to the grinding activity is an important parameter in the overall utilization for each machine. Under the current scenario for the self-steering trailer, the turnaround is located before the grinder allowing a truck to wait in the turnaround rather than at the turnout near the unit entrance. This reduces the distance a truck must drive once the grinder is free. A disadvantage of this setup is that the truck must backup from the turnaround to the grinder location and may limit the system if the distance is long or the road conditions challenging. As mentioned earlier, the advantage of the self-steering trailers over a standard chip van is the ability to use the trailer as the steering mechanism while backing, making it easier to navigate. Also, the backing speed of the self-steering trailer is faster (5 mph) than a standard chip van (2 mph) allowing for a quicker maneuver.

A sensitivity analysis was done to evaluate the distance from the turnaround to the grinder affects the overall utilization for the grinder and the total cost **(**Figure FL-5.19**).** The number of available trucks in the base case was set to five trucks and the distance from the turnaround to the grinder location varied from 0.05 miles (264 feet) to 1 mile. Total cost increased by $7.02 BDT^{-1} when changing the distance from 0.05 miles to 1 mile. The grinder utilization decreased from 66% at 0.05 miles to 50% at a 1 mile distance. The closer the grinder is to the turnaround, the less time the truck had to wait at the turnaround or turnout near the unit entrance reducing the transportation cost. Also, the grinder utilization increased due to shorter backing lengths. The greater the distance, the more time a truck had to wait at the turnaround increasing the transportation cost. The backing distance was also increased, reducing the grinder utilization.

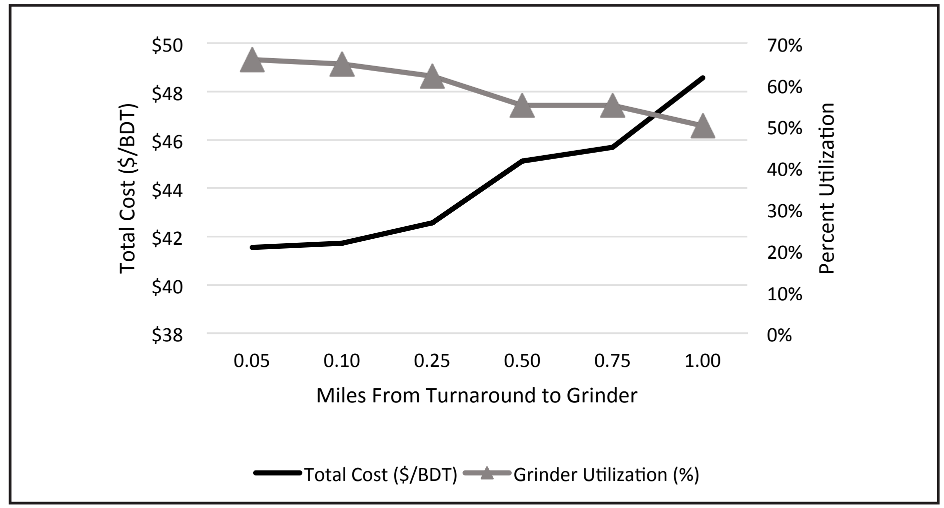

Figure FL-5.19. Sensitivity analysis of total cost and grinder utilization to changes in the distance from the turnaround to the grinder location under the self-steering system. Cost are expressed in US dollars per bone dry ton ($/BDT).

The distance to the end facility is another factor in the overall utilization for each machine. By changing the distance between the harvest unit entrance and the end facility, the round-trip time will either increase or decrease. This could alter machine interactions and thus change working and waiting cost of the equipment. By altering the round-trip time of the transportation, the number of cycles in the system could change, affecting the grinder utilization. A sensitivity analysis was completed to look at how changing the distance to the end facility from the unit entrance affects the grinder utilization and the total cost (Figure FL-5.20). There were five trucks available under this scenario with the distance to the end facility varying from 10 miles to 70 miles. The results of the operation conclude that total cost increased by $18.90 BDT^{-1} when changing the distance to the end facility from 10 miles to 70 miles. As the distance to the facility increased, the number of cycles decreased due to the trucks not having enough time to return to the unit. It was observed that at the 10 and 20 mile distances the waiting time for the trucks increased as the interaction between trucks was more frequent upon arrival to the unit. On the other hand, the increased distance to the facility reduced truck interaction but limited the number of loads through the system. The grinder utilization under this scenario decreased from 79% (10 miles) to 52% (70 miles).

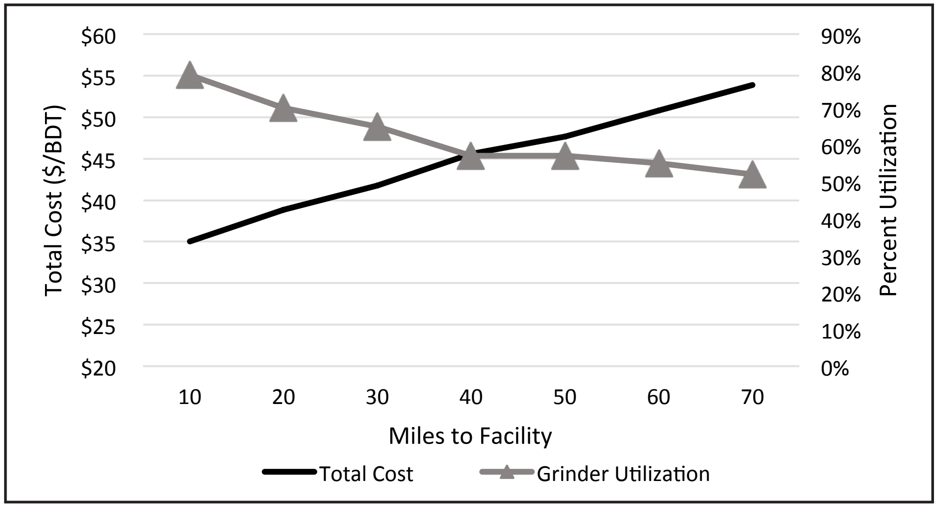

Figure FL-5.20. Sensitivity analysis of total cost and grinder utilization to changes in the distance to the end facility under the self-steering system. Cost are expressed in US dollars per bone dry ton ($/BDT).

Hook-lift trucks provide another way of utilizing forest harvest residues located in areas with limited road access. These smaller, more flexible trucks provide a way to access remote locations (Han et al., 2008). Typically, the hook-lift application is used with a central location within or near the harvest unit and is limited by the distance the hook-lift truck must travel due to its small load and high cost per ton-mile. Han et al. (2009) reported that the central location should ideally be less than five miles from the harvest sites. An advantage of using a central location is the ability to draw from multiple harvest units reducing the mobilization cost of the system. For example, the grinder does not have to move to each unit individually, but rather can remain at the central location. However, the central location can be limited if there is not enough space for the incoming forest residues.

In most cases, the hook-lift application may require more equipment than other transportation methods, such as the self-steering system, increasing the total cost of the operation. For example, as the hook-lift trucks bring material to the central location, they are limited to how high the residuals can be piled. A second loader may be required to arrange the material as it comes in to the central landing to increase the efficiency of the grinder. Grinding can be completed as the material comes in or delayed. The grindings can be either processed directly into a standard chip van or piled. If the grindings are piled at the central location, then a wheeled loader is required to load the chip vans as they arrive.

In the modeled hook-lift application, the costs include both the primary stage and secondary stage costs. The primary stage cost is the accumulation of the loader cost (in-woods loader + central area loader) and the hook-lift transportation cost. The in-woods loader was assumed to be continually moving and rearranging piles when not filling bins. Each bin was 40-cubic yards and had an average weight of 5.32 GT (3.52 BDTs) and took 14 minutes to fill. The working time of the secondary loader at the central area is dependent on the distance it must travel to move the pile as well as the height of the pile. It was assumed that each load took 14 minutes to move and rearrange. The waiting time of the secondary loader was dependent on how long it was in the system and its working time per shift. Similar to the self-steering model, the hook-lift truck working time is dependent on its inter-arrival time, round trip time, and number of cycles completed. Under the base case scenario, the truck waiting time is based on any waiting time (if any) at the turnout before the loader. If a hook-lift truck arrives at the turnout and there is another truck already at the in-woods loader location, then the truck must wait until the other truck drops the empty bin, picks up the loaded bin, and then drives past the turnout location.

The secondary stage cost is the sum of the processing and transportation cost. Like the self-steering system, the processing cost is dependent on the working and waiting times in a shift of the loader and grinder. The transportation cost is dependent on the average working and waiting times in a shift of the standard trailer multiplied by the number of trailers in the system. A 53-ft standard trailer was used to transport the material to the end facility and was assumed to have a loading time of 32 minutes with a capacity of 31.24 GTs.

Hook-Lift System Costs

$$PS = C_L + C_{HL} \quad (18)$$
$$C_L = (IW_L + (W_L * H_L) + (WTC_L * Y_L)) / BDTs \quad (19)$$
$$C_{HL} = ((W_{HL} * H_{HL}) + (WTC_{HL} * Y_{HL}) * N) / BDTs \quad (20)$$
$$SS = K_p + Q_T \quad (21)$$
$$K_p = (((W_L + W_G) * H_{LG}) + ((WTC_L + WTC_G) * Y_{LG})) / BDTs \quad (22)$$
$$Q_T = ((W_{ST} * H_{ST}) + (WTC_{ST} * Y_{ST}) * N) / BDTs \quad (23)$$

Where:

PS total cost of primary stage in a hook-lift application, ($/BDT)

C_L total cost of loaders in hook-lift application, ($/BDT)

C_{HL} total cost of hook-lift transportation, ($/BDT)

IW_L total cost of in-woods loader in a hook-lift application, ($)

H_L working time of loader at central area in a hook-lift application, ($/hr)

Y_L waiting time of loader at central area in a hook-lift application, ($/hr)

W_{HL} hourly working cost of hook-lift trucks, ($/hr)

H_{HL} working time of hook-lift trucks, (hr)

WTC_{HL} hourly waiting cost of hook-lift trucks, ($/hr)

Y_{HL} waiting time of hook-lift trucks, (hr)

SS total cost of secondary stage in a hook-lift application ($/BDT)

K_p total processing cost at central area in a hook-lift application, ($/BDT)

Q_T total secondary transportation cost in a hook-lift application, ($/BDT)

W_{ST} hourly cost of a standard chip van in a hook-lift application, ($/hr)

H_{ST} working time of a standard chip van in a hook-lift application, (hr)

WTC_{ST} hourly waiting cost of a standard chip van in a hook-lift application, ($/hr)

Y_{ST} waiting time of a standard chip van in a hook-lift application, (hr)

A hook-lift application was modeled under the base case (Figure FL-5.17) to compare the total cost and efficiency of the system to the self-steering trailer. Under this scenario only one harvest unit provided material to the central location, as opposed to Han et al. (2009), which had several harvest units providing material. It was assumed that the grinding application took place after all the harvest residues were brought to the central location and was directly processed into 53-ft standard chip vans. At the central landing, there were three chip vans available with the distance to the end facility set to 30 miles. A loader was needed in the woods to fill the bins with a second loader at the central location piling the residues as they were delivered. The round-trip time was much less for the hook-lift trailers as compared to the self-steering chip vans because the travel distance was shorter. A shorter round-trip time may increase the number of cycles during a shift, but can also increase machine interactions and therefor increase the system cost.

A sensitivity analysis was done to look at the effect of the number of available hook-lift trucks to total cost and efficiency (Figure FL-5.21). Results from the analysis are that two trucks minimized the primary transportation cost ($48.44 BDT^{-1}) with 23 loads delivered to the central location. The primary transportation cost for three trucks was $59.30 BDT^{-1} delivering 24 loads to the central location. Having only one truck available was the more expensive option under this scenario delivering 14 loads to the central location at a cost of $61.17 BDT^{-1} for the primary transportation. At the central location, the secondary transportation cost plus processing totaled $37.26 BDT^{-1} delivering nine loads to the end facility.

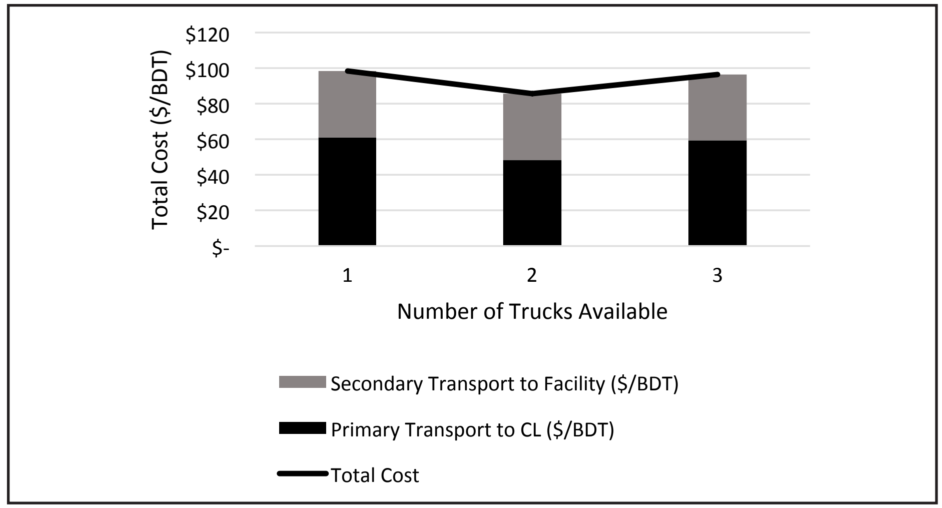

Figure FL-5.21. Total cost of the primary and secondary stages in hook-lift application with variable number of trucks available. Cost are expressed in US dollars per bone dry ton ($/BDT).

A sensitivity analysis was completed to evaluate how altering the distance between the harvest unit and the central location affects the total cost and efficiency (Figure FL-5.22). Two hook-lift trucks were available to transport material with the same setup at the central location. The distance between the harvest unit and the central location varied from 1-4 miles. Total cost increased from $85.70 BDT^{-1} (one mile) to $102.93 BDT^{-1} (4 miles), showing that the distance between the central location and harvest unit is an important factor in determining whether a hook-lift application will be more economical than an alternative system such as the self-steering chip van.

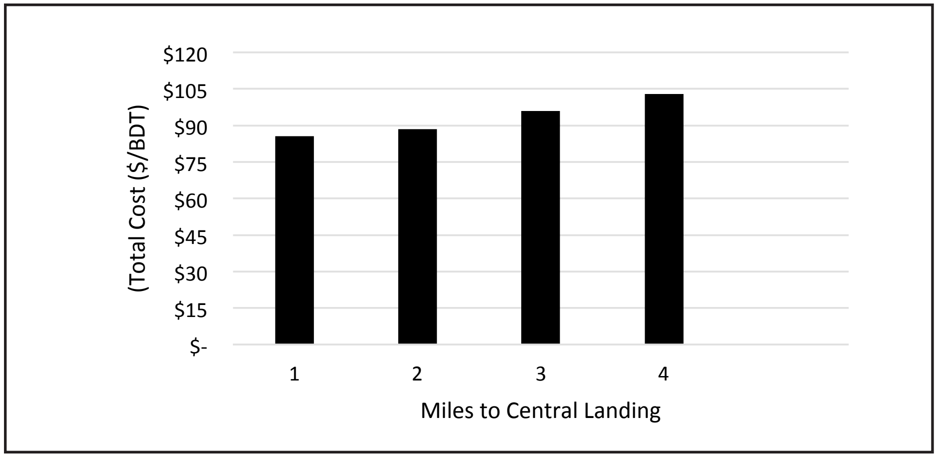

Figure FL-5.22. Sensitivity analysis of the total cost to changes in the distance to the central landing under the hook-lift application. Costs are expressed in US dollars per bone dry ton ($/BDT).

Mobilization and piling cost were added to account for total system costs. Mobilization cost is sensitive to the total amount of biomass transported to the end facility during the whole operation and not just under the shift duration. The piling cost is sensitive to the time a machine moved, re-arranged, or touched harvest residues to prepare an area for the grinder operation and the total amount of biomass transported to the end facility. Under the base case scenario, it was assumed that 350 BDTs were moved, piled, and transported to an end facility. For the self-steering option, the processing and transportation cost were $41.76 BDT^{-1} with a piling cost of $8.57 BDT^{-1} and a moving cost of $4.11 BDT^{-1}. The total system cost for the self-steering trailer system option was $54.44 BDT^{-1}. For the hook-lift application, a piling cost was not added, as the in-woods loader was assumed to be rearranging material in-between filling bins. There was a higher mobilization cost for the hook-lift application ($6.17 BDT^{-1}) than the self-steering option, because more equipment was needed with the same amount of biomass being transported to the end facility. The total processing and transportation cost under the hook-lift application was $85.70 BDT^{-1} and after adding the mobilization cost the total system cost was $91.87 BDT^{-1}.

Not all material will require a hook-lift truck. Some fraction of the landings could be accessible by a standard 45-ft chip van so that a grinder could be mobilized to the roadside landing. Thus, some combination of hook-lift trucks and standard trailers might be used. An analysis was done to see how the total cost of the hook-lift system changes if a percentage of the transportation type was reserved for using a 45-ft standard chip van with a capacity of 25.68 GT (16.95 BDTs). The hourly cost for a 45-ft chip van ($110.63 hr^{-1}) was less than the self-steering chip van and is hypothesized that reserving some of the area for a standard trailer will reduce the hook-lift application total system cost. This is under the assumption that some of the area (changes with percent allocation) in the harvest unit is accessible using a standard chip van. Also, the same round-trip time was assumed for the standard chip van as it was for the self-steered trailer. The self-steering trailer remained less expensive than the combination system (Figure FL-5.23) until the allocation for the hook-lift trucks was reduced to around 12% (88% allocation to the standard chip vans). Hook-lift trucks are sensitive to the distance they must travel as well as the carrying capacity of the bins.

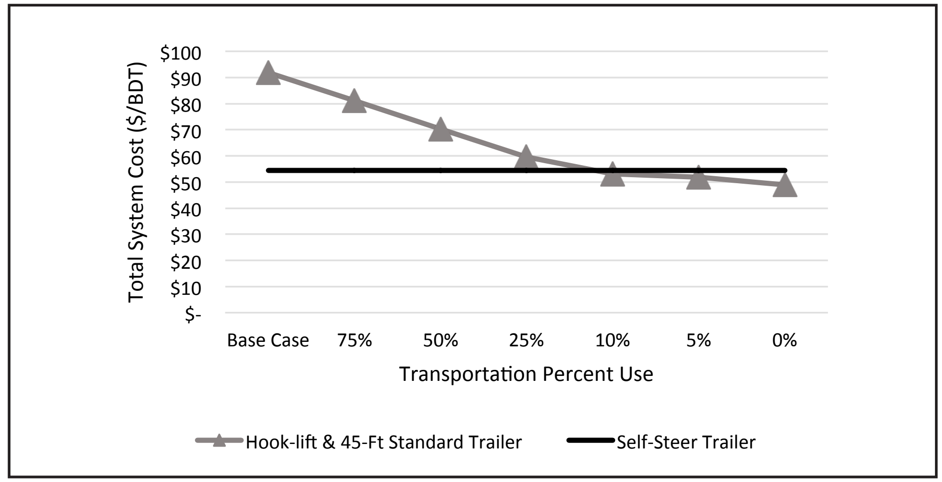

Figure FL-5.23. Comparison of the total cost for the combination system (hook-lift truck + 45 ft standard chip van) to the self-steering system with regards to changing the percent allocation of the hook-lift truck. As hook-lift truck percent use (x-axis) decreases, the allocation of hook-lift trucks is reduced and standard chip van use increased. The analysis used the base case parameters.

To evaluate the sensitivity of reducing the distance from the turnout to the grinder/loader and increasing the bin load, the bin truck travel distance was reduced to 1 mile and the specific gravity of material being transported (larger pieces, heavier species) was increased to 0.47. Under these assumptions, the self-steering system remained less costly ($50.20 BDT^{-1}) than the hook-lift application but the margin narrowed and the breakeven point was 21% (Figure FL-5.24). The combined hook-lift, standard trailer combination system was not competitive with the self-steering system until the allocation of the standard chip van was high enough to offset the limitation of having more equipment in the field and limited capacity of the hook-lift trucks.

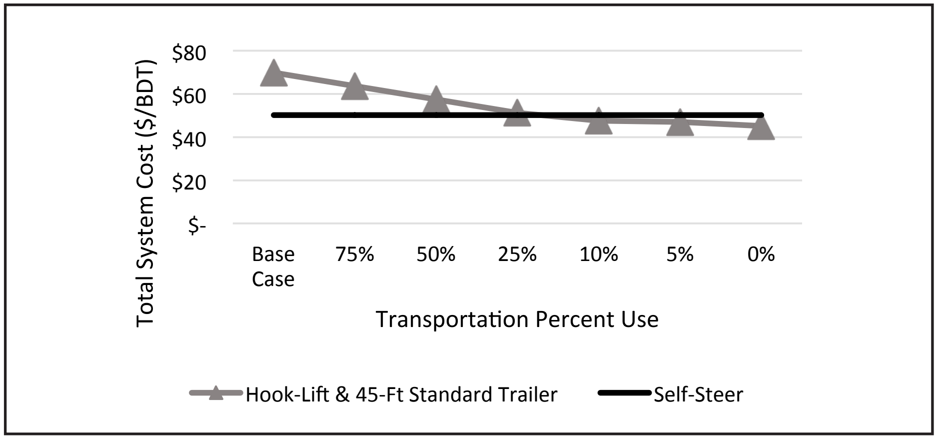

Figure FL-5.24. Comparison of the total cost for the combination system (hook-lift truck + 45 ft standard chip van) to the self-steering system with regards to changing the percent allocation of hook-lift truck. Base case parameters except that distance from the turnout to the grinder was reduced to 1.0 mile and specific gravity of the residues was increased to 0.47.

3.6. Concluding Remarks

Large chip van trailer access to reach harvest residues can be challenging as roads were generally designed for stinger-steered log trucks. Field tests and modeling of the self-steer trailer system show that it can competitive with other transportation options. The self-steering trailer required less area to turn on both road intersection type turnarounds as well as landing-based turnarounds. For the landing-based turnarounds, a 53 x 80-foot area should be adequate to turn around a 48-ft self-steering trailer with a 60 x 90-foot area being adequate to turn around a standard trailer. For the road intersection type turnarounds, the self-steering trailer could successfully turn around in areas that were too limiting for the standard trailer. Pairing a 6x6 truck with the self-steering trailer allowed the vehicle to navigate off-road giving it more room if needed. Under the type of road conditions tested out in the field the average turn around time for the self-steering trailer was around 4 minutes.

Arena Simulation by Rockwell Automation was used to model the self-steering system against a hook-lift application to compare their cost effectiveness on a total system cost BDT^{-1} basis. The simulation was used to derive working and waiting machine times. A cost model was created to calculate an hourly machine cost to determine the total system cost when considering working and waiting times. Under the base case scenario, the self-steering system was lower cost than the hook-lift application with a total system cost, including mobilization and piling, of \$54.44 BDT^{-1}. The hook-lift application total cost was \$91.87 BDT^{-1}. Assuming a 45-ft standard trailer could reach a percentage of the harvest unit, the combination system was not competitive under the base case scenario until the percent allocation for the hook-lift trucks reduced to about 12%. After favoring the hook-lift application by reducing the distance in the base case from the turnout to the grinder/loader to 1 mile and increasing the specific gravity of the material to 0.47, the self-steering system was still more cost effective until the allocation for hook-lift trucks was reduced to about 21%.

4. Economics of Double Trailers in Transporting Forest Biomass on Steep Terrain

Trucks with larger single trailers are often not able to travel on forest roads due to narrow roads, tight curves, adverse grades and limited areas to turn around (Zamora and Sessions, 2015). Shorter trailers are then used to transport processed biomass, but their capacity is often limited by the trailer volume due to the low bulk density of the comminuted biomass, particularly when the biomass is dry. They can also be limited by allowable legal weight based on axle number and spacing. In this section we explore the economic feasibility of using double truck-trailer configurations to transport forest biomass in Washington, Oregon and California. We compare the use of doubles to single trailers when processing the material at the landing or in centralized yards.

Trailer capacity is a function of the truck power train, trailer dimensions, transportation regulations, and bulk density of the processed biomass. Transport cost is a major component of biomass delivered cost. High diesel prices have increased transportation costs, triggering interest in effective strategies to reduce the unit cost per transported ton. One strategy is to increase dry weight per trip by reducing the moisture content of forest residues through natural drying in the forest before comminution (Ghaffariyan et al., 2013; Roser et al. 2011). But, when material is dry (moisture content<30% wet basis), trailers frequently become limited by volume capacity and not by allowable gross weight (Roise et al., 2013). This is due to the low bulk density of the dry wood particles and problems associated with the loading method in the traditional conveyor-fed (gravity drop) system used with horizontal grinders (Zamora-Cristales et al., 2014). Increasing hauling capacity by using larger trailers is often the most intuitive alternative. However, in mountainous terrain operations, steep adverse grades, weight restricted bridges and tight curves can limit the ability to drive larger single trailers to the comminution site (Angus-Hankin et al., 1995). Several trailer designs have been developed to improve access for large single trailers including sliding axle trailers, stinger-steered trailers, and self-steered trailers (Sessions et al. 2010), and decision support systems have been developed to help decide where road improvements might be made to accommodate various types of single trailers (Beck and Sessions, 2013). An alternative to larger or modified single trailers is the use of double trailers. A double trailers system consists of one truck pulling two short trailers that can be decoupled to allow transportation of single trailers on steep roads. Double trailers are common on major highways for moving many types of bulk products, including wood chips, but are rare in mountainous terrain. In this report, we focus on examining under what conditions double trailers might be competitive compared to single trailers under the legal restrictions of Oregon, Washington, and California.

The maximum gross load for any truck-trailer configuration in Oregon and Washington is 105,500 lb and for California 80,000 lb (WSDOT, 2014; ODOT, 2014; CALTRANS, 2014), but can be lower depending on truck-trailer configuration. The legal limit for each truck-trailer configuration is determined by the number of axles and axle spacing combinations of the truck-trailer combination, load per axle, and tire width. The use of double trailers, compared to single trailers, offers an alternative to avoid being volume limited and can maximize load capacity up to the legal gross weight limits when transporting dry material. Legal load limits for double trailers usually are higher than the legal weight for single trailers due to their greater number of axles and axle spacing. Double trailers can either be loaded directly at a centralized site that provides adequate access for double trailers, or they can be decoupled at a hook-up site and transported singly to the processing site. The lower-weight, shorter trailers can negotiate tighter curves, steeper grades, and can turn around in shorter spaces. In this section, the main objective is to analyze the economic feasibility of using double trailers in forest biomass operations on steep terrain. We analyzed under which conditions double trailers will become cost-effective compared to single trailers and what are the potential operational disadvantages and limitations. The scope of the study is for operations in California, Oregon and Washington. Double trailers are rarely used in current biomass operations because moisture content of the residues is often high enough that trucks pulling single trailers are weight limited, but as moisture management strategies are implemented we expect more trailers to become volume limited. We analyzed the applicability of double trailers based on length and weight regulations of the individual states. We applied a simulation model to understand the dynamic of truck arrivals and quantify the effect of waiting times in productivity that will be difficult to estimate using a static cost method. In steep terrain conditions, usually one truck can access the processing site at a time, thus if other truck is entering the site it must wait for the other truck to be loaded first. The amount of wait time will be dependent on the arrival time of each truck.

4.1. Truck-trailer Modeling

A biomass operation in steep terrain usually consists of a grinder that is placed at a landing where forest harvest residues have been piled by a swing-boom loader as part of the logging operation. Trucks arrive at the landing to be loaded and travel back to the bioenergy facility. We developed a simulation model that explores the productivity and performance of the grinder and trucks operation. The information for the simulation model was obtained by observing current operations in southwestern Oregon. We recorded 58 productive cycles using GPS units in each truck. We also applied the continuous time method (Pfeiffer, 1967), to record in-forest loading. In these operations we analyzed productivity of a tri-axle truck tractor pulling two 32 ft (feet) trailers and one tri-axle tractor pulling single trailers of different lengths ranging from 32 to 45 feet long. A 45-ft long trailer is the longest conventional single trailer commonly used in steep terrain. It requires about the same road width around curves as two 32-ft double trailers, depending on how the two trailers are coupled. In all harvest units the roads were single lane gravel with road gradients ranging from 5 to 20%. Parameters analyzed for double trailers and the respective units were: (1) travel speed loaded on paved roads in miles per hour (mph); (2) travel speed unloaded on paved roads (mph); (3) travel speed loaded on gravel roads (mph); (4) travel speed unloaded on gravel roads (mph); (5) hook-up time for a tractor to trailer in minutes (min); (6) hook-up time first trailer-dolly-second trailer (min); (7) loading rate at the forest in tons per minute (tons/min); and (8) unloading rate at the bioenergy facility (tons/min), (Table FL-5.3).

Table FL-5.3. Average operational parameters for single and double trailers obtained from time and motion studies in different forest biomass operations, standard deviation in parentheses.

Activity	Double truck-trailer configurations	Single truck-trailer configurations
Traveling Loaded Paved (mph)	41.7 (1.36)	46.9 (1.74)
Traveling Unloaded Paved (mph)	43.4 (1.34)	49.5 (0.81)
Traveling Loaded gravel (mph)	15.0 (1.85)	14.9 (0.37)
Traveling Unloaded gravel (mph)	15.5 (1.73)	15.6 (0.73)
Hook-up tractor-trailer (min)	4.0 (0.47)	-
Hook-up trailer-dolly-trailer (min)	6.4 (0.85)	-
Loading (tons/min)	0.97 (0.05)	0.99 (0.05)
Unloading (tons/min)	0.50 (0.06)	0.72 (0.04)

In general, doubles speed is 11% lower than singles on paved roads and singles unloading rate is 1.5 times faster than doubles. The slower speed can be related to the increased weight and length in doubles, the latter may limit maneuverability resulting in lower speed. The longer unloading time is due to the fact that the second trailer must be decoupled prior to unloading since only one trailer can be unloaded at a time using typical trailer designs and unloading facilities in the Pacific Northwest. Furthermore, the doubles require additional time to hook and unhook single trailers to take them to the processing landing where the grinder is located. We analyzed whether the increased volumetric and weight capacity offered by the doubles can compensate for the increased time (and cost) per trip spent by this configuration compared to the use of single trailers. Truck-trailer configurations were modeled in the Java language using a simulation library developed by Helsgaun (2000). The system dynamics was modeled as discrete events for each activity in the transportation cycle time.

4.2. Economics of Transportation

The economics of transportation was analyzed by calculating the hourly costs by state (traveling unloaded, traveling loaded or idle) and multiplying them by the time spent in each of the activities in the transportation cycle (traveling loaded, traveling unloaded, loading and unloading times). Truck fuel consumption and cost was calculated using an engineering approach that looks at the vehicle performance in order to calculate the power required to overcome rolling and air resistance. The power required to overcome these two forces was then translated into fuel consumption (Wong, 2008; Douglas, 1999). It was assumed a frontal area of the truck of 100 ft^2 and an air drag coefficient equal to 1 (Caterpillar, 2006). Using this approach, we accounted for differences in weight and travel speed by state (traveling unloaded or loaded) and between configuration types (doubles or singles trailers). We also accounted for the truck standing cost that applied when the truck is being loaded or unloaded. This cost included labor, insurance and taxes expenses only, since it was assumed that the driver turned off the truck's engine when the truck is idle. Grinding cost was estimated at $454/h when processing and $119/h when standing waiting for trucks to arrive. Similar costs are reported by Coltrin et al. (2012). Total cost was then divided by the dry tonnage processed and transported to obtain the dollars per bone dry ton ($/BDT).

4.3. Model Assumptions

Two double truck-trailer and three single trailer configurations were selected to compare the performance of double trailers performance with those of a broad range of single trailer sizes. The double trailer configurations were selected because they maximize legal weight and length and at present are the current largest configurations used to carry forest biomass in Oregon and Washington. It consists of a 6x6 tri-axle tractor (510 hp) pulling two 32 ft long trailers with a single trailer capacity of 2700 ft^3 (cubic feet), or 5,400 ft^3 total. In Oregon, this configuration can carry up to 105,500 lb (pounds) with a low cost extended weight permit. In most routes in Oregon, there is no limit to the overall length of the tractor-trailer combination, however each trailer shall not be longer than 40 feet and the two trailers shall not measure more than 68 feet from front to rear (including the space between the trailers). Similar length restrictions apply to Washington State with the only difference that both trailers measuring more than 61 feet need a special permit up to 68 feet. In terms of weight, Washington Department of Transportation establishes a limit of 105,500 lb. No extended weight permit is needed. The second configuration applies to California and consists of a 6x6 tri-axle tractor (500 hp) pulling two 28 ft long trailers with a single trailer capacity of 2200 ft^3, or 4400 ft^3 total. This configuration has a maximum allowable weight of 80,000 lb. Doubles are allowed to operate on California roads as long as each trailer's length do not exceed 28 feet 6 inches. Maximum overall length is restricted to 75 feet (CALTRANS, 2014).

Maximum legal weight for the two double tractor-trailer configurations analyzed was calculated based on the State regulations, the number and distance between axles and a network programming model formulated by Sessions and Balcom (1989) using the Federal Bridge Gross Weight Formula (Federal Highway Act of 1974, as amended). Maximum volumetric capacity was calculated using the trailer manufacturer volume specifications and the bulk density of the material. The parameters obtained for the double trailer configurations were compared to three single trailer configurations of 32, 42, and 45 feet long respectively to reflect the available range of trailer sizes across the region.

The limiting capacity (volumetric and weight) for each trailer configuration was determined for Douglas-fir grindings at a bulk density of 12.4 lb/ft^3, with an average moisture content of 20% (wet basis). This density was estimated from 64 samples of field dried biomass and calculated by adapting ASTM International (2013) standard E873-82. At the assumed density the limiting factor for all single trailer configurations was volume. For double trailer configurations the legal weight was the limiting factor (Table FL-5.4).

Table FL-5.4. Truck-trailer capacity limiting factors.

Item	Doubles 32-32 ft	Doubles 28-28 ft	Singles 45 ft	Singles 42 ft	Singles 32 ft
Truck-Trailer weight (tons)	20.5	18.0	16.0	15.6	14.3
Maximum legal weight (tons)	52.5	40.0	44/40*	40	36.8
Maximum payload (tons)	32.0	22.0	28.0/24*	24.5	22.5
Trailer volumetric capacity (cubic feet)	5,400	4,400	3,510	3,240	2,700
Trailer adjusted capacity at 12.4 lb/ft^3 (tons)	32	22	21.8	20.1	16.7
Limiting factor	Weight	Weight	Volume	Volume	Volume

*Limits apply to California only

Results from the system dynamics model allowed us to calculate cost based on the cost matrix for each of the selected options (Table FL-5.5). We simulated two scenarios; double trailers at the forest landing and double trailers at a centralized yard. In each scenario, we modeled productivity and cost of the 32-32 ft double trailer configuration (for Oregon and Washington), 28-28-ft double trailer configuration (for California) and the 32, 42 and 45 ft single trailer configurations.

Table FL-5.5. Transportation costs, ($/h) for double and single truck-trailer configurations. Higher hourly costs on paved roads than on gravel roads were related to higher speeds and fuel consumption per hour.

Truck-Trailer Configuration	Paved	Gravel	Standing
Doubles 32-32 ft Empty	99.42	78.06	41.32
Doubles 32-32 ft Loaded	126.09	88.30	41.32
Doubles 28-28 ft Empty	95.32	74.96	40.74
Doubles 28-28 ft Loaded	113.51	81.67	40.74
Single 45 ft Empty	90.27	70.30	40.44
Single 45 ft Loaded	108.30	77.01	40.44
Single 42 ft Empty	87.75	68.36	39.86
Single 42 ft Loaded	104.37	74.56	39.86
Single 32 ft Empty	85.35	66.49	39.28
Single 32 ft Loaded	101.89	81.63	39.28

4.4. Grinding at the Landing

This first scenario modeled used four double trailers to reach the processing/grinding landing in the forest and compared them to the productivity and cost of using four single trailers. In this scenario for the double trailers, one trailer has to be decoupled at an accessible hook-up point and then single trailers are transported to and loaded at the processing landing where the grinder is located (Figure FL-5.25).

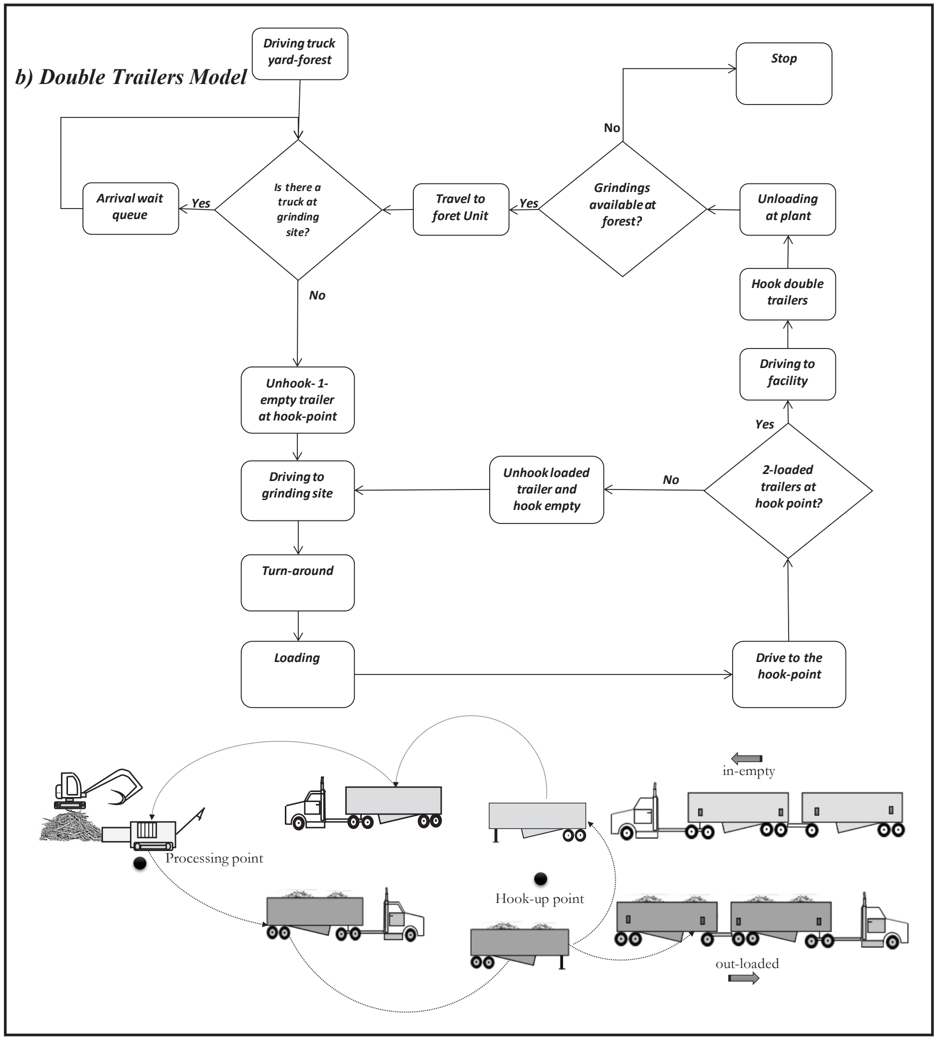

Figure FL-5.25. Grinding at the landing, double truck-trailer configuration model with hook-up point.

The use of double trailers to reach the grinding landing (comminution site) in steep terrain involves: (1) driving unloaded to harvest unit hook-up point and unhook one of the single trailers; (2) drive the first single trailer unloaded to the comminution site; (3) load the first single trailer; (4) drive the first loaded trailer from the comminution site to the hook-up point; (5) detach the first loaded trailer; (6) hook-up the second unloaded trailer, drive the second unloaded trailer to the comminution site and load the second single trailer; (7) drive the second loaded trailer from the comminution site to the hook-up point and attach the dolly and hook the first loaded trailer; (8) drive the loaded double trailers to the bioenergy facility; (9) unhook one of the trailers; (10) unhook the empty trailer and hook-up the loaded trailer; (11) hook-up the second empty trailer and drive back unloaded to the hook-up point in the forest. Under these conditions double trailer configurations spent an average of 34% more time compared to singles for a single roundtrip. The majority of the extra time is due to the time double trailer configurations spent in the forest decoupling and transporting individual trailers from the processing site to the hook-up point. Additional time was also involved in decoupling at the unloading site. The two key variables of this scenario affecting the double truck-trailer configuration economics are the distance from the hook-up point to the bioenergy facility and the distance from the hook-up point to the grinding landing. We performed a sensitivity analysis of productivity and cost by adjusting one of the variables and leaving the other fixed.

Assuming a fixed distance of one mile from the hook-up point to the grinding landing, we varied the distance from the hook-up point to the bioenergy facility from 10 to 100 miles. For Oregon and Washington, results indicated the double trailer configuration 32-32 feet can be cost effective at distances from the hook-up point greater than 35 miles when comparing with the single 32 ft trailer; 56 miles for the single 42 ft trailer and 70 miles for the single 45 ft trailer (Figure FL-5.26). Although the hourly cost of double trailers is more expensive (21% higher) and the time spent in a single trip is higher (by 34%), their higher capacity (92% higher compared to the single 32 ft; 59% higher compared to the single 42 ft and 47% higher compared to the single 45 ft), makes them a cost effective option at greater distances. However, for California, double trailers do not appear to be a cost effective alternative when comparing with the single truck trailer configurations, mainly because the gain in payload (32% when compared to single 32 ft, 9% when comparing with single 42 ft and 1% when comparing with the 45 ft alternative) does not compensate for the increased hourly cost and time spent per trip (Figure FL-5.27). Although the volumetric capacity for this configuration could accommodate up to 27.3 tons of payload, regulations allow only 22 tons after accounting for the tractor and trailer weight. Lighter trailers would to increase capacity, but legal weight may still be the limiting factor.

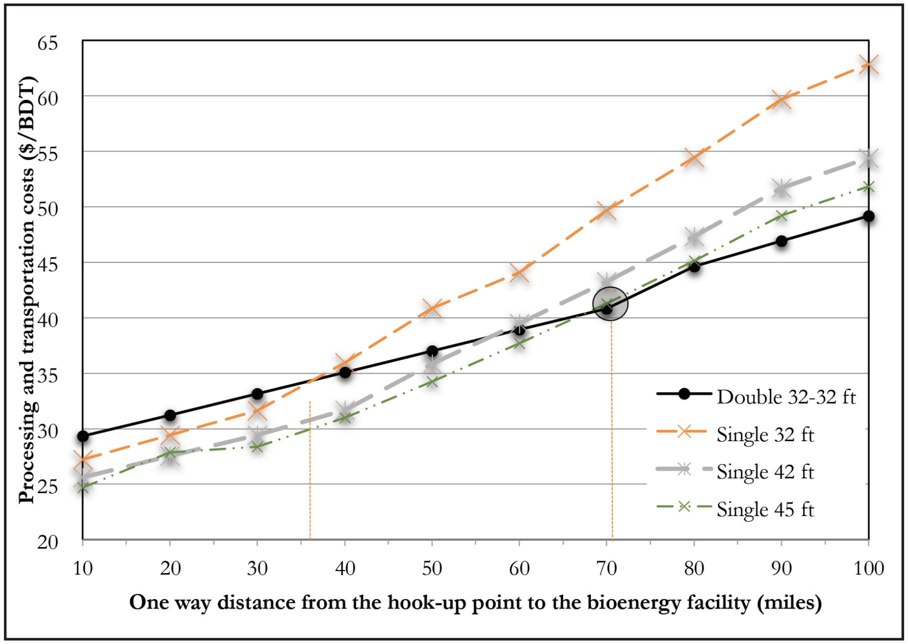

Figure FL-5.26. Sensitivity of cost to distance of singles compared to the double trailer configuration 32-32 ft suitable for Oregon and Washington.

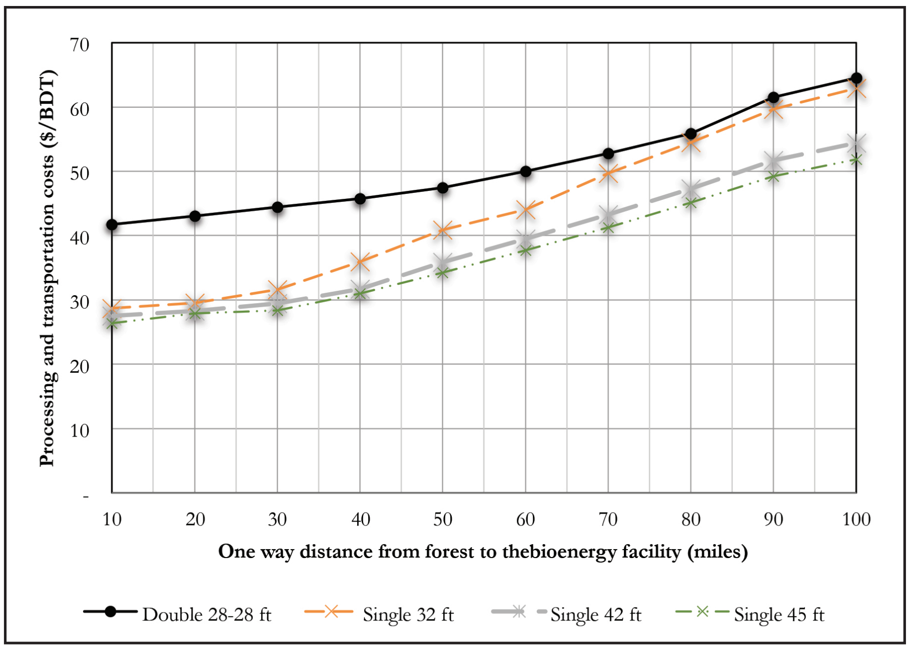

Figure FL-5.27. Sensitivity of double truck trailer configuration 28-28 ft economics to changes in distance between the hook-up point and the bioenergy facility for California for biomass at 20% moisture content.

We used the upper breakeven mileage bound as the fixed value for the distance from the hook-up point to the bioenergy facility (70 miles), and we varied from 0.5 to 5 miles the distance from the hook-up point to the landing to analyze the sensitivity of the double trailer economics to this factor. For Oregon and Washington the choice of double trailer configuration versus the single 42 and 45 feet alternatives is sensitive to small distance changes. If distance between the hook-up point and the grinding landing is greater than 1 mile, then the single 45 ft configuration becomes more cost effective. Similarly, if we increase the distance to two miles then the double trailer configuration becomes more expensive than the single 42 ft option (Figure FL-5.28).

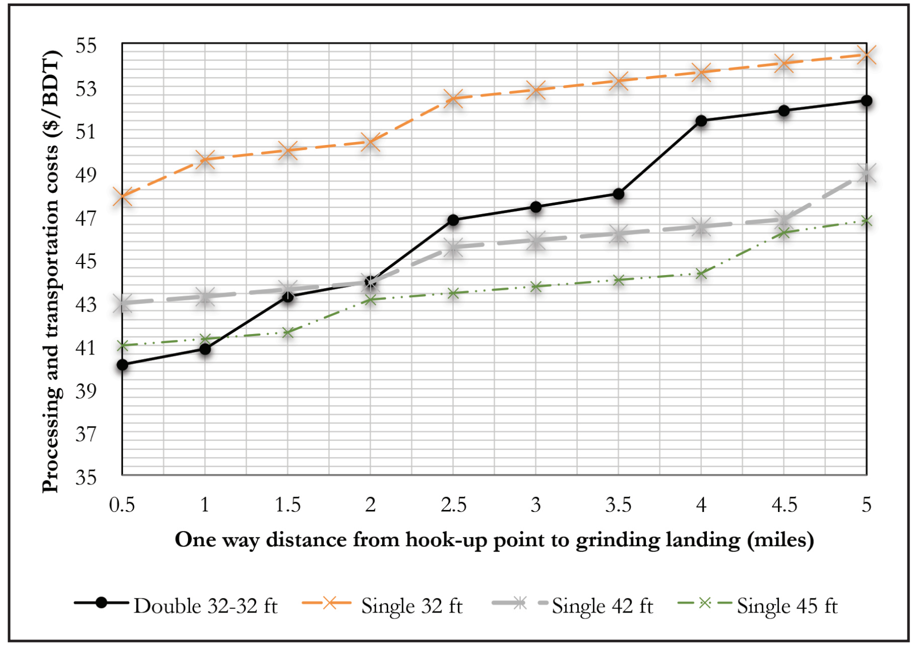

Figure FL-5.28. Sensitivity of cost for 32-32 ft double truck trailer configuration to changes in distance between hook-up point and grinding landing.

4.5. Grinding at a Centralized Yard

This scenario considers the use of a centralized yard to process the material and thereby decouples grinding from transportation to the bioenergy facility, avoiding grinder wait times for chip van arrival and trailer exchange. In this scenario the grinder processes and dumps the material directly into a pile (not depending on trucks), and trucks are loaded independently with material from the pile using a front-end loader. It was assumed that the double truck-trailer configuration can be loaded onsite without the need to unhook trailers, and the centralized yard has enough space to allow the doubles to turn around (Figure FL-5.29). Unprocessed residues are transported from the forest to the centralized yard using short trucks such as bin trucks or hook-lift trucks. In this scenario the key variable is the distance from the centralized yard and the bioenergy facility. We varied this parameter from 10 to 100 miles.

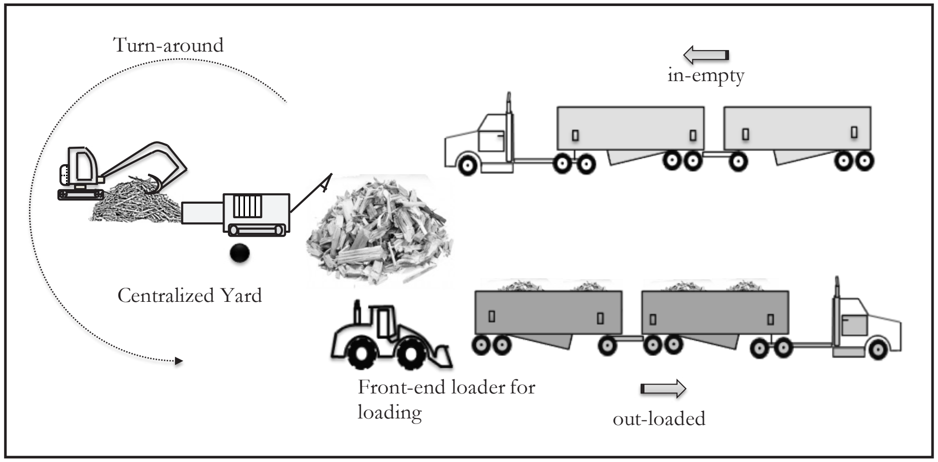

Figure FL-5.29. Centralized yard, double truck-trailer configurations working around the centralized location.

Productivity and cost of the double trailer configurations at a centralized yard was compared to normal grinding operations at the landing using single trailers. By comparing singles trailers working at the landing and double trailers working at the centralized yard we were able to calculate the marginal benefit of using double trailers. Transporting the material from the centralized yard to the bioenergy facility is cheaper compared to loading the trailer at the forest landing, however the centralized yard requires transport of the unprocessed residue from the forest to the centralized landing for grinding.

Results for this scenario showed that the 32-32 ft double trailer configuration for Oregon and Washington had savings ranging from $4.4/BDT to $12.4/BDT, depending on the distance from the centralized yard to the forest (Figure FL-5.30). These values can be interpreted as maximum amount that could be paid for transporting the unprocessed residues from the forest to the centralized yard. In the Oregon, bin trucks cost about $70 per hour and have a capacity ranging between 5 and 10 tonnes, similar hourly costs for California have been reported by Harrill et al., (2009). Bisson et al. (2015) in a study in northern California reported that a converted articulated dump truck carried about 5.6 BDT per load of unprocessed residues at a cost of about $4.5 per BDT per mile plus about $6.5/BDT to load the dump truck. The 28-28 ft double trailer configuration for California offers few improvements and it is only cost effective when compared with the 32 ft single trailer configuration.

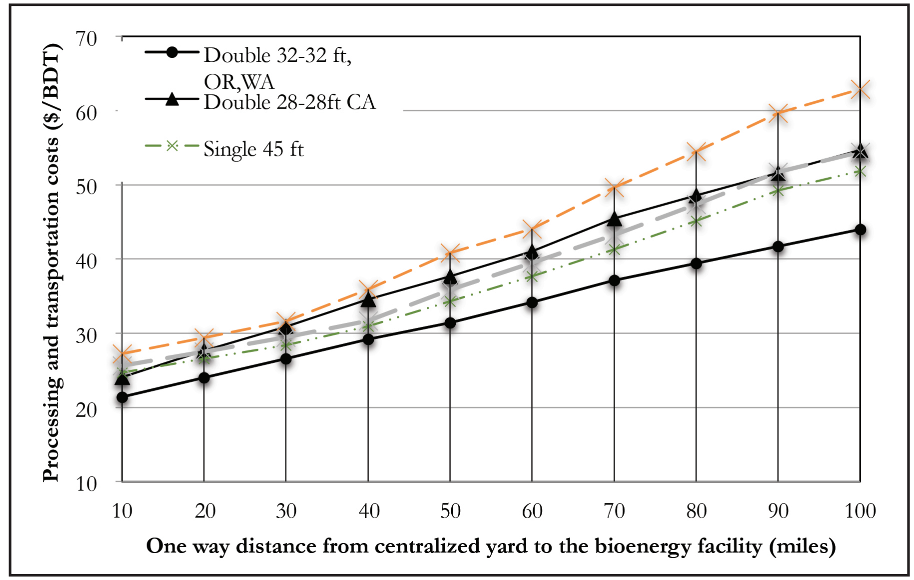

Figure FL-5.30. Processing and transportation cost of double trailer configuration at a centralized yard and single trailers at the grinder landing.

4.6. Concluding Comments

Both double trailer configurations analyzed in this analysis offer a gain in volumetric capacity, however the current regulations in California severely impact the potential use of double trailers in that State for transporting forest biomass. Lighter trailers can help to increase the potential payload but probably not up to the tonnages allowed in Oregon and Washington.

When processing at the grinding landing, the key variables affecting the performance of double trailers are the distance from the hook-up point to the bioenergy facility and the distance from the grinding landing to the hook up point. For Oregon and Washington, it is clear from the results that as distance from the hook-up point to the bioenergy facility increases, double trailers have the potential to become cost-effective alternatives. This is because transport time increases with the distance so the relative cost per ton favors doubles in long distance hauls. On the other hand, as distance from the hook-up point to the grinder landing increases, double trailers becomes a less feasible option because of the lower payload between the landing and the hook-up point and the additional hooking time.

In the case of the centralized yard, savings are reported because the grinding does not depend on transportation and double trailers do not need to be decoupled, thus, they function as single trailers. However, the transportation of unprocessed residues is expensive because of the heterogeneous nature of the residue (branches, tops and log butts), and productivity can be affected by the traveled distance. Also if material is not already piled at roadside additional cost of collection may apply.

In summary, the future of doubles seems limited to longer hauls to more distant processing centers and only then if hook-up points are close to the grinding landing. The current efforts in improving trailer maneuverability for larger single trailers, 48-53 ft in length, and in increasing dry bulk density may offer more potential for reducing transport cost.

5. Road Modifications for Large Trailer Access

5.1. Types of Road Modifications

As discussed in Section 2 (Chip Trucks and Chip Vans), many forest road systems in the western United States have been developed for long-log, stinger-steered log trucks (Sessions et al. 2010). An alternative to the use of specialized trailers is to make temporary or permanent road modifications to permit large trailer access. These choices include temporarily filling the ditch, removing or reversing the superelevation to reduce lateral tire slip, and widening the roadway. During the dry months, temporarily filling the ditches or changing the superelevation of the roadway are options that permit specialized vehicles access. Temporarily filling the ditch provides a greater road width for the specialized vehicle to pass, usually 0.5 to 1.5m of extra road width. Single lane forest roads surfaces are insloped, outsloped, or crowned. Positive superelevation of the road surface is often constructed into forest roads to counteract centrifugal force created by vehicles in curves (Oglesby and Hicks, 1982). Negative superelevation of the road surface is sometimes constructed into curves to adjust the normal forces on the driving axles to permit climbing steeper grades (Anderson and Sessions, 1991). Outsloping a forest road is sometimes used to drain water from the road surface without diverting water to ditches, and insloping of forest roads is done for safety when roads are icy (Bowers, 2006). During the dry months, superelevation may not be needed either because side friction is greater and/or cross slope drainage is not an issue; providing an opportunity to alter the road surface to reduce lateral tire slip toward the inside of a curve. Two options exist when altering the superelevation: (1) remove the superelevation and (2) reverse the superelevation. Removing the superelevation reduces the amount of off-tracking that a vehicle produces by reducing the amount of lateral tire slip due to gravity (Glauz and Harwood, 1991). Reversing the superelevation could be used to counteract off-tracking; allowing the weight of the vehicle and the effects of gravity on an inclined plane to counter the effects of off-tracking. Lastly, forest engineers and managers can affect the outcome by redesigning the roadway to allow these vehicles access along the entire roadway length. This is achieved by widening the roadway and removing obstacles close to the roadway such as standing trees.

Each modification option has an associated cost and benefit. For example, if a 13.7m drop center 5^{th}-wheel chip van (Figure FL-5.31) needs an extra half meter of road width to access a harvest unit, the ditches might be temporarily filled to allow the 5^{th}-wheel chip van access. If the ditches were not filled, the only vehicle that might have access to the unit would be a stinger-steered chip trailer (Figure FL-5.32). Not only does the amount of off-tracking vary between vehicles, so does the volume of chips or hogfuel consistent with weight restrictions that these vehicles can haul. The operating cost and traveling speed vary for each vehicle configuration, creating a multi-dimensional problem.

Figure FL-5.31. A 13.7m drop center 5th-wheel chip van being loaded on a forest road in Lane County, Oregon.

Figure FL-5.32. A stinger-steered chip van. Photo courtesy of Western Trailer Company.

5.2. Two Case Studies

We look at two cases. The first case involves scheduling multiple biomass operations over a road network where trucks from several biomass operations can take advantage of the same road investment. The second case looks at isolated biomass operations where the road investment is used by only one operation. For both cases, mixed integer linear programming can be used to exactly solve the underlying mathematical problem. However, for the second case, it is more convenient to use a breakeven analysis. For larger problems of the first case, due to the solution time for mixed integer programming, heuristics such as Ant Colony Optimization (ACO) can be used to determine a high quality solution for vehicle type, path, and road modifications for transporting biomass. Other useful heuristics are described by Glover and Kochenberger (2002), Hoos and Stutzle (2005) and Geem (2009).

5.2.1. Case One

The mathematical problem is to minimize the sum of road modifications and biomass transportation costs. Let G=(N,A) be a directed network with nodes N and arcs (i,j) within A. We associate with each node i within N a number S(i) which indicates the supply or demand depending on whether S(i) > 0 or S(i) < 0. The minimal cost problem is then:

Minimize

$$\sum_{(i,j)\in A} FC_{ij}^t x Y_{ij}^t + \sum_{(i,j)\in A}\sum_{t\in T} VC_{ij}^t \cdot Volume_{ij}^t \quad \forall\,(i,j)\in A, t\in T \qquad [24]$$

Conservation of Flow

$$\sum_{\{ji(i,j)\in A\}} Volume_{ij}^t - \sum_{\{ji(j,i)\in A\}} Volume_{ji}^t = V^t(i) \quad \forall\, i\in N \qquad [25]$$

Sale Volumes

$$\sum_{t\in T} V^t(i) = S(i) \qquad \forall\; i\in N \qquad [26]$$

Road Triggers

$$\sum_{t\in T} M\,x\,Y_{ij}^t \geq Volume_{ij}^1 \qquad \forall\,(i,j)\in A \qquad [27]$$

$$\sum_{t\in T\,(t\geq 2)} M\,x\,Y_{ij}^t \geq Volume_{ij}^2 \qquad \forall\,(i,j)\in A \qquad [28]$$

$$\sum_{t\in T\,(t=3)} M\,x\,Y_{ij}^t \geq Volume_{ij}^3 \qquad \forall\,(i,j)\in A \qquad [29]$$

Decision Variables

$$Y_{ij}^t = \{0,1\} \qquad \forall\,(i,j)\in A, t\in T \qquad [30]$$

$$Volume_{ij}^t \geq 0 \qquad \forall\,(i,j)\in A, t\in T \qquad [31]$$

Equation [24] is the objective function. FC_{ij}^t is the fixed cost to modify link *ij* to allow truck type *t* access. is a binary variable, zero if the link is not used, and one if the link is used. is the round trip variable cost over link *ij* in truck type *t*, ($/tonne). $Volume_i^t$ is the amount of volume crossing link *ij* in truck type *t*, (tonnes). Equation [25] provides conservation of flow at each node for each truck type. $V^t(i)$ is the volume entering each node *i* for each truck type *t*, (tonnes). Equation [26] requires that the total supply or demand at each node *S(i)* (tonnes) equal the sum of the volume transported over all truck types. Equation [27] requires that the road modification for truck type *1* (the lowest standard truck type) be made to at least pass truck type *1* if there is volume passing over link *ij* in truck type *1*. Equation [28] requires that the road modification for truck type *2* (the moderate standard truck type) be made to at least pass truck type *2* if there is volume passing over link *ij* in truck type *2.* Equation [29] requires that the road modification for truck type *3* (the highest standard truck type) be made to pass truck type *3* if there is volume passing over link *ij* in truck type *3.* Equation [30] requires that the road trigger for link *ij* for truck type *t* be a binary variable, zero or one. Equation [31] requires that the volume passing over link *ij* for truck type *t* be equal to or greater than zero.

5.2.1.1. Ant Colony Optimization

The ACO (Dorigo and Stutzle, 2004) is based on the analogy of ants searching for food. Ants randomly walk in search of food leaving a pheromone behind as they travel. The pheromone is a scent that influences other ants to take that path. As more ants travel over the same path, the pheromone increases, increasing the possibility of an ant choosing that path. This process continues until all ants are following the same path to the food source. The ACO heuristic has been used to solve fixed cost and variable cost forest transportation problems with side constraints (Contreras et al., 2008). Outside of the forest industry, this heuristic has been used to solve vehicle route scheduling problems, capacitated vehicle routing problems, and other scheduling problems (Donati et al., 2008; Rizzoli et al., 2007).

5.2.1.2. Application of ACO to Small Problem

The ACO developed in Case I is designed to minimize the total transportation cost. The total transportation cost is the sum of the modifications costs plus the round trip variable costs multiplied by the volume of each harvest unit. If a truck is loaded at sale *x*, it must make it to destination *z* using the same truck. If different types of trucks use the same link, the one with the maximum fixed cost will be applied. Therefore, if road modifications are applied so that a 16.2m drop center 5th-wheel chip van (Figure FL-5.33) can navigate the road, no other modifications need to take place for other truck types. The ACO regards each road modification option as a separate link. In other words, between each node three links exist; one that has no fixed cost, one that has a moderate fixed cost, and one that has a large fixed cost; all of which end up at the same node (Figure FL-5.34). As the algorithm progresses through each set of ants, each ant in each set has a designated modification option that it will choose from as it progresses through the network. It was chosen to have three kinds of ants; a truck type *1* ant, a truck type *2* ant, and a truck type *3* ant to diversify the search. With this formulation, each modification option has its own set of pheromones. The starting pheromones provided an equal probability choosing each link leaving a node for each truck type. As the algorithm identifies a lower total cost route from each sale, the links that are not part of that path have their pheromones decay. We used a constant decay factor of 25 percent.

Figure FL-5.33. A 16.2m drop center 5th-wheel chip van near Port Angeles, Washington.

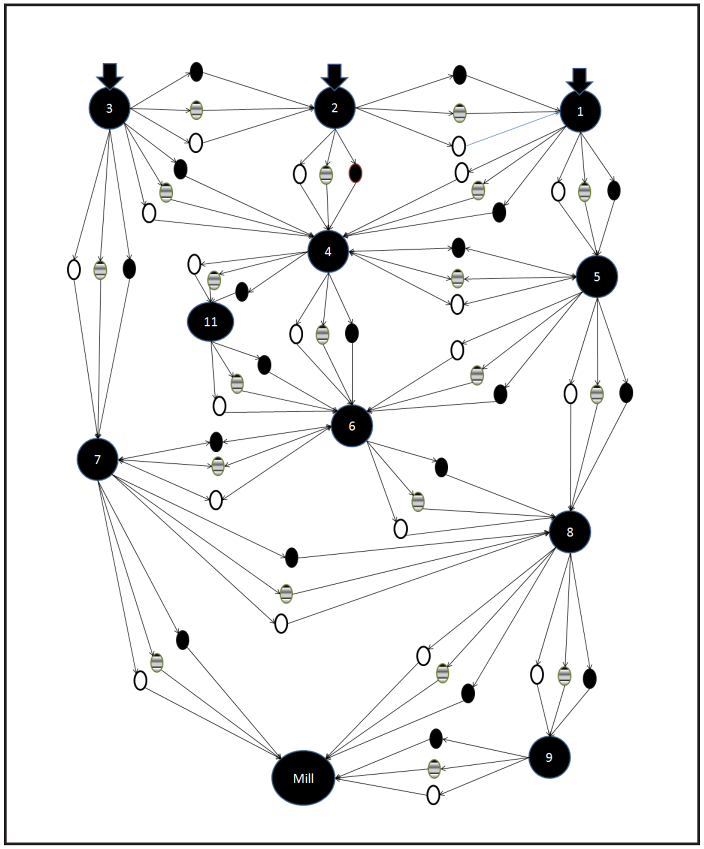

Figure FL-5.34. Small example road network with modification alternatives, adapted from (Sessions, 1985).

The ACO was compared to a mixed integer linear programming model, using a small network (Figure FL-5.34). The large black circles are the nodes in the network. The small black circles are the road modification option for the 16.2m drop center 5th-wheel chip van, the small horizontally hatched circles are the road modification option for the 13.7m drop center 5th-wheel chip van, and the small white circles are the no road modification option for the stinger-steered chip van. In this formulation, three different degrees of road modification could be applied, no modification, moderate modification, or major modification. The no modification option will only allow a stinger-steered chip van access. The moderate modification option will allow a stinger-steered chip van and a 13.7m drop center 5th-wheel chip van access. The major modification will allow all three trucks access to the road segment. Each truck has a different hourly operating cost. The stinger-steered chip van has an estimated hourly cost of $95.37, the 13.7m drop center 5th-wheel chip van hourly cost is $90.95, and the 16.2m drop center 5th-wheel chip van hourly cost is $99.79 (Table FL-5.6). We assumed cost per hour is the weighted average hourly cost and did not vary with speed or road type.

Table FL-5.6. Chip Van Operating Characteristics for the three truck types.

Trailers	Volume Capacity, m^3	Kilometers per Hour on Forest Roads (empty or loaded)	Kilometers per Hour on Highways (empty or loaded)	Operating Cost, $/hr	Modification Cost, $/km
12.8m Stinger Steered	73.6	16.1	72.4	$95.37	$0
13.7m Drop Center 5th-wheel	93.4	16.1	72.4	$90.95	$3,281
16.2m Drop Center 5th-wheel	113.3	16.1	72.4	$99.79	$9,843

The modification costs vary by the magnitude of the required modifications. The moderate modification option was assumed to require removing the superelevation within the roadway and filling the ditches to allow the 13.7m drop center 5th-wheel chip van access. We assumed that these modifications would cost $3,281 per km. The major modification option was assumed to require filling the ditches, reversing the superelevation, and widening the roadway on a few select curves. These modifications were estimated to cost $9,843 per km (Table FL-5.6). We assumed that only half of the link length needed to be modified because on a forest road curves are approximately half of the transportation network.

The sale nodes for the small network (Figure FL-5.34) are nodes 1, 2, and 3. The associated amount of biomass for each sale (chips or hogfuel) is identified in Table FL-5.7. All of the biomass is to be delivered to only one mill (Node 10). The haul and modification costs per link are provided in Table FL-5.8.

Table FL-5.7. Sale Nodes for the Small Network.

Volume of Biomass		
Harvest Node	Destination Node	Biomass, m^3
1	10	135,921
2	10	28,883
3	10	175,564

Table FL-5.8. Haul and Modification Cost for the Small Network.

Link Identifier		Truck Type	Round Trip Haul Cost $/Truck/Link	Modification Cost $/Link
From	To			
1	4	12.8m Stinger	18.79	0
1	4	13.7m Drop Center 5^{th}-wheel	17.91	2,600
1	4	16.2m Drop Center 5^{th}-wheel	19.66	7,800
1	5	12.8m Stinger	6.14	0
1	5	13.7m Drop Center 5^{th}-wheel	5.86	850
1	5	16.2m Drop Center 5^{th}-wheel	6.43	2,550
2	1	12.8m Stinger	12.28	0
2	1	13.7m Drop Center 5^{th}-wheel	11.71	1,700
2	1	16.2m Drop Center 5^{th}-wheel	12.85	5,100
2	4	12.8m Stinger	6.14	0
2	4	13.7m Drop Center 5^{th}-wheel	5.86	850
2	4	16.2m Drop Center 5^{th}-wheel	6.43	2,550
3	2	12.8m Stinger	9.39	0
3	2	13.7m Drop Center 5^{th}-wheel	8.96	1,300
3	2	16.2m Drop Center 5^{th}-wheel	9.83	3,900
3	4	12.8m Stinger	6.50	0
3	4	13.7m Drop Center 5^{th}-wheel	6.20	900
3	4	16.2m Drop Center 5^{th}-wheel	6.80	2,700
3	7	12.8m Stinger	6.32	0
3	7	13.7m Drop Center 5^{th}-wheel	6.03	875
3	7	16.2m Drop Center 5^{th}-wheel	6.61	2,625
4	5	12.8m Stinger	9.03	0
4	5	13.7m Drop Center 5^{th}-wheel	8.61	1,250
4	5	16.2m Drop Center 5^{th}-wheel	9.45	3,750
4	6	12.8m Stinger	6.14	0
4	6	13.7m Drop Center 5^{th}-wheel	5.86	850
4	6	16.2m Drop Center 5^{th}-wheel	6.43	2,550
4	11	12.8m Stinger	4.34	0
4	11	13.7m Drop Center 5^{th}-wheel	4.13	600
4	11	16.2m Drop Center 5^{th}-wheel	4.54	1,800
5	4	12.8m Stinger	7.95	0
5	4	13.7m Drop Center 5^{th}-wheel	7.58	1,100
5	4	16.2m Drop Center 5^{th}-wheel	8.32	3,300
5	6	12.8m Stinger	3.61	0
5	6	13.7m Drop Center 5^{th}-wheel	3.45	500
5	6	16.2m Drop Center 5^{th}-wheel	3.78	1,500
5	8	12.8m Stinger	6.14	0
5	8	13.7m Drop Center 5^{th}-wheel	5.86	850
5	8	16.2m Drop Center 5^{th}-wheel	6.43	2,550
6	7	12.8m Stinger	5.42	0
6	7	13.7m Drop Center 5^{th}-wheel	5.17	750
6	7	16.2m Drop Center 5^{th}-wheel	5.67	2,250
6	8	12.8m Stinger	6.50	0
6	8	13.7m Drop Center 5^{th}-wheel	6.20	900
6	8	16.2m Drop Center 5^{th}-wheel	6.80	2,700
7	6	12.8m Stinger	1.81	0
7	6	13.7m Drop Center 5^{th}-wheel	1.72	250
7	6	16.2m Drop Center 5^{th}-wheel	1.89	750
7	8	12.8m Stinger	6.50	0
7	8	13.7m Drop Center 5^{th}-wheel	6.20	900
7	8	16.2m Drop Center 5^{th}-wheel	6.80	2,700
7	10	12.8m Stinger	9.03	0
7	10	13.7m Drop Center 5^{th}-wheel	8.61	0
7	10	16.2m Drop Center 5^{th}-wheel	9.45	0
8	9	12.8m Stinger	5.06	0
8	9	13.7m Drop Center 5^{th}-wheel	4.82	700
8	9	16.2m Drop Center 5^{th}-wheel	5.29	2,100
8	10	12.8m Stinger	19.51	0
8	10	13.7m Drop Center 5^{th}-wheel	18.60	0
8	10	16.2m Drop Center 5^{th}-wheel	20.41	0
9	10	12.8m Stinger	9.03	0
9	10	13.7m Drop Center 5^{th}-wheel	8.61	0
9	10	16.2m Drop Center 5^{th}-wheel	9.45	0
11	6	12.8m Stinger	0.36	0
11	6	13.7m Drop Center 5^{th}-wheel	0.34	50
11	6	16.2m Drop Center 5^{th}-wheel	0.38	150

Table FL-5.8. Haul and Modification Cost for the Small Network.

The ACO had a stopping criterion of 1,000 iterations. The heuristic converged on its solution rather quickly (iteration 282). The optimal solution to this problem using the ACO is $72,140. This amounted to $6,225 in modification costs and $65,915 in hauling costs. The optimal path is shown for each sale in Table FL-5.9 and Figure FL-5.35. There were 1,454 trips from Unit 1 to the Mill, 309 trips from Unit 2 to the Mill, and 1,550 trips from Unit 3 to the Mill.

Table FL-5.9. The Optimal Path for the Small Network Using Ant Colony Heuristic.

Total Cost	$72,139.50	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
13.7m Drop Center 5th-wheel	13.7m Drop Center 5th-wheel	16.2m Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3
5	4	7
6	11	10
7	6	
10	7	
	10	

The ACO solution was compared to a mixed integer solution (Table FL-5.10; Figure FL-5.35). The mixed integer and ACO produced identical solutions with only small total cost differences due to rounding when formulating the mixed integer problem. Both methods used the same truck types and paths to transport the biomass to the mill. This small example illustrates that the heuristic appears reasonable for determining near optimal solutions for similar road modification problems.

Table FL-5.10. The Optimal Path for the Small Network Using Mixed Integer Programming.

Total Cost	$72,154.26	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
13.7m Drop Center 5th-wheel	13.7m Drop Center 5th-wheel	16.2m Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3
5	4	7
6	11	10
7	6	
10	7	
	10	

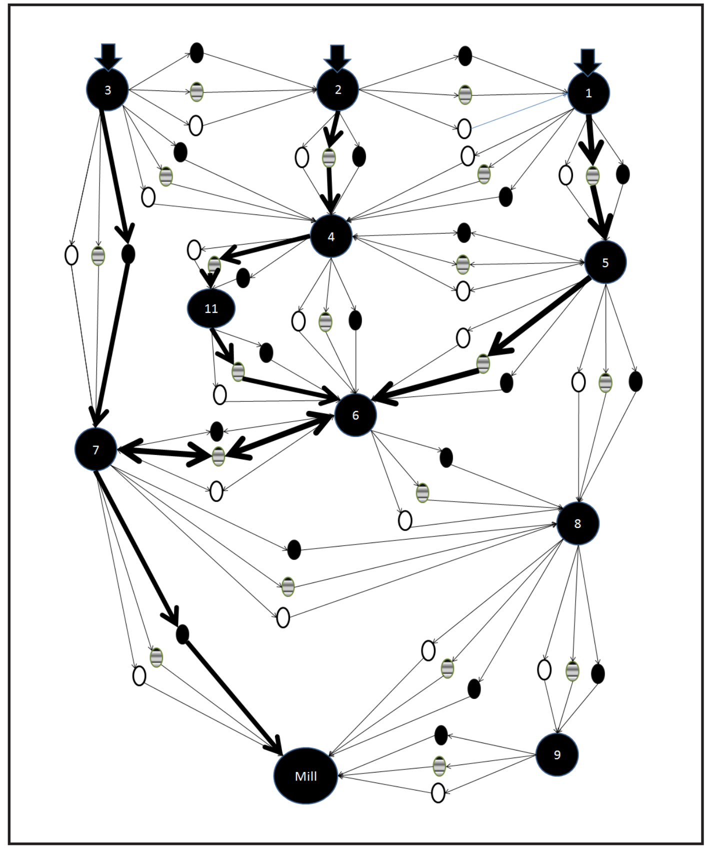

Figure FL-5.35. Optimal haul routes. The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification oprion for the 16.2m drop center 5th-wheel chip van, the small horizontally hatched circles indicate the road modification option for the 13.7m drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

5.2.1.3. Application to a Realistic Forest Transportation Network

Following the favorable results on the small network, the ACO heuristic was used on the McDonald Forest, to determine the least cost path for future harvesting activities. McDonald Forest, a teaching, research and demonstration forest, is located 11.3km north of Corvallis and is managed by the College of Forestry, OSU (Figure FL-5.36). Several biomass-powered cogeneration plants exist within 95km of McDonald Forest. A major cost of biomass operations is the transportation cost. With small profit margins, it is important to determine the least cost method for transporting biomass from the woods to the mill. Being able to determine the optimal trucks and haul routes that would reduce total transportation costs would be important to the decision to utilize biomass. We applied the ACO heuristic to develop a least cost path from a sample of harvest units distributed through McDonald Forest. McDonald Forest is approximately 2,914ha with 113km of road or about 37.3m of forest roads per hectare (Lysne, D. and Klumph, B. OSU College

Forests, Corvallis, Oregon, Personal Communication, December 14, 2011). The McDonald Forest road network and possible truck routes through Corvallis are shown in Figure FL-5.36.

Thirty hypothetical timber harvests (sales) were spread through McDonald Forest (Figure FL-5.36) for the purpose of reducing fuel loading around the urban interface. These timber harvests were assumed to produce and recover 89.7 green tonnes of

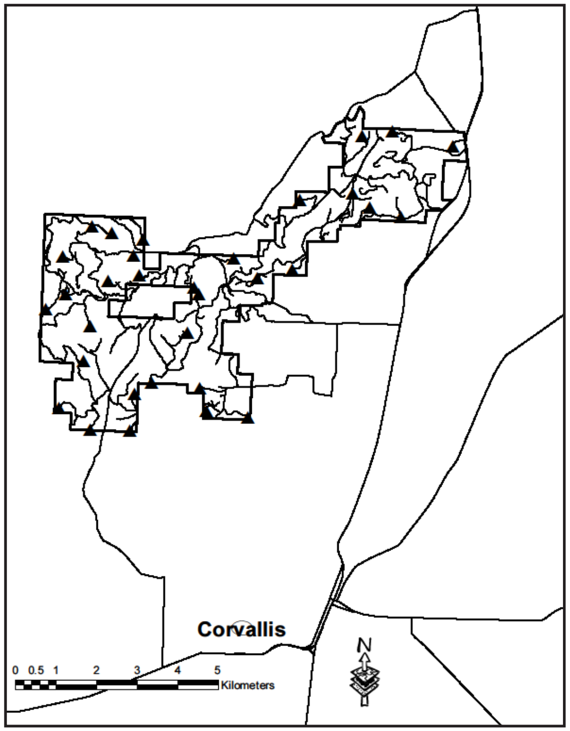

Figure FL-5.36. McDonald Forest Road Network, Corvallis, Oregon, USA. The black triangles are the sale nodes.

biomass per hectare or 113.3m^3 of biomass with 50 percent moisture content. It was estimated that each sale would harvest between 45 and 95ha (black triangles in Figure FL-5.36). The destination node for all of the transported biomass is a biomass plant in Eugene (48km south of Corvallis). The estimated travel speed on forest roads was 16.1km/h and 72.4km/h on major highways (loaded or unloaded). On public highways, it was assumed that any truck combination could be used without incurring any road modification costs. The transportation network included 405 nodes and 2,433 links, including the existing transportation network and two modification options for each link. The existing transportation network was assumed to only permit stinger-steered trailer access. The other two trailer types required temporary road modification for access similar to the small network problem. The chip van operating characteristics in this problem are the same as shown in Table FL-5.6. Once the chip vans were outside of the McDonald Forest, it was assumed that any chip van could be used without incurring a road modification cost. It was also assumed that adequate turnarounds exist to permit use of each truck type. The routes for the 30 sales produced by the ACO in 10,000 iterations are shown in Figure FL-5.37. For every sale, the ACO determined the least cost path used a 16.2m drop center 5th-wheel chip van. The total transportation cost was $2,697,920 with $254,647 in road modification costs and $2,443,273 in haul costs. The road modification costs amount to nine percent of the total cost. If no road modifications had been made, only the stinger steered chip van could have been used with a total transportation cost of $3,703,310 (100 percent haul costs). In this example, the ability to modify the roadway to allow larger trucks access to these sales reduced the total transportation cost by 27 percent. The ability to reduce transportation costs by 27 percent is a large benefit when margins are as slim as they are in the biomass market. This implies that being able to reduce the haul cost with the application of road modifications could have a significant positive impact.

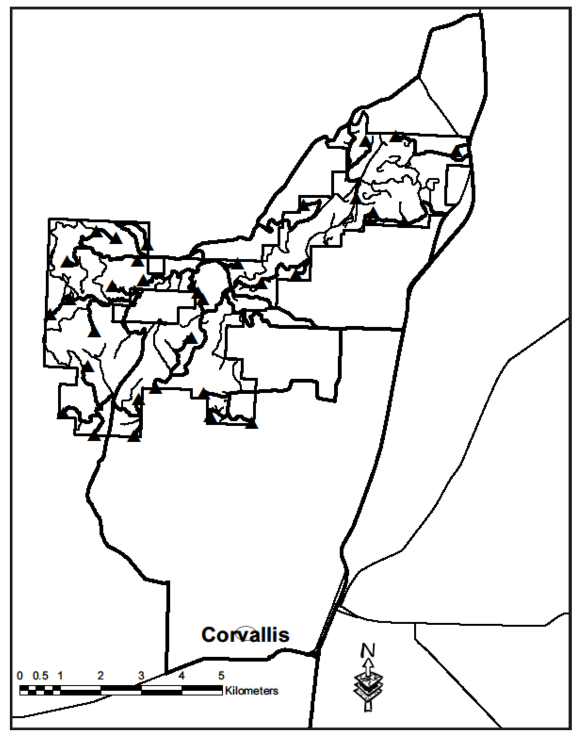

Figure FL-5.37. Optimal set of paths for all 30 sales, McDonald Forest, Corvallis, Oregon, USA.

5.2.2. Case Two

Case I provided an example of how several biomass recovery sites and the use of road modifications can reduce overall transportation costs when considering road investments that benefit where there are several biomass sites sharing a common network. However, the ability to have nearby residue sites may not be practical. For the case of isolated sites, we provide a decision-making framework to assist in deciding the optimal truck type. When comparing cost per tonne versus highway haul kilometers, the 16.2m drop center 5th-wheel chip van is the most economical (Figure FL-5.38). However, if the forest transportation network requires modification, the most economical chip van changes. For illustration, we assume that loaded and empty vehicles of a given type travel at the same speed and have the same hourly cost (Table FL-5.6). The cost per tonne including transport and road investment is:

$$Cost\ Per\ Ton_t = \frac{2\ x\ HK \cdot OC_t}{KPH_{H_t} \cdot VC_t} + \frac{2 \cdot FK \cdot OC_t}{KPH_{F_t} \cdot VC_t} + \frac{FK \cdot PFK_t \cdot MC_t}{H \cdot V} \qquad \forall\, t \in T \qquad [32]$$

Where:

HK = distance traveled on highway roads (one-way km)
FK = distance traveled on forest roads (one-way km)
OC_t = operating cost of chip van, t ($/hr)
VC_t = volume capacity of chip van, t (tonnes)
KPH_{Ht} = average operating speed on highway roads for chip van, t (km/h)
KPH_{Ft} = average operating speed on forest roads for chip van, t (km/h)
PFK_t = percentage of the forest road kilometers that need to be modified for chip van, t
MC_t = forest road modification cost for chip van, t ($/km)
V = harvest volume per hectare (tonnes/ha)
H = total harvest area (ha)

Equation 32 can be manipulated to compare alternative truck options for the single sale. For example, the breakeven highway haul distance (the highway distance that provides the same cost per tonne between two trucking options) can be calculated for any two trucking options:

$$HM= \frac{FK\ x \left(\frac{2 \cdot OC_b}{KPH_{F_b} \cdot VC_b} + \frac{PFK_b \cdot MC_b}{H \cdot V} - \frac{2 \cdot OC_a}{KPH_{F_a} \cdot VC_a} - \frac{PKM_a \cdot MC_a}{H \cdot V} \right)}{\left(\frac{2 \cdot OC_a}{KPH_{H_a} \cdot VC_a} - \frac{2 \cdot OC_b}{KPH_{H_b} \cdot VC_b} \right)} \qquad [33]$$

The subscripts "*a*" and "*b*" indicate the two trucking options being compared. Equation 33 assumes that both truck options can be operated on the highway. Some counties may have restrictions over some roads that do not permit trucks or trailer combinations over a maximum length or weight.

The breakeven equation between the 12.8m stinger-steered chip van and the 16.2m drop center 5th-wheel chip van if no road investment is required is trivial (Figure FL-5.38). The cost per tonne in the 16.2m drop center 5th-wheel chip van is always lower than the cost per tonne in the 12.8m stinger-steered chip van.

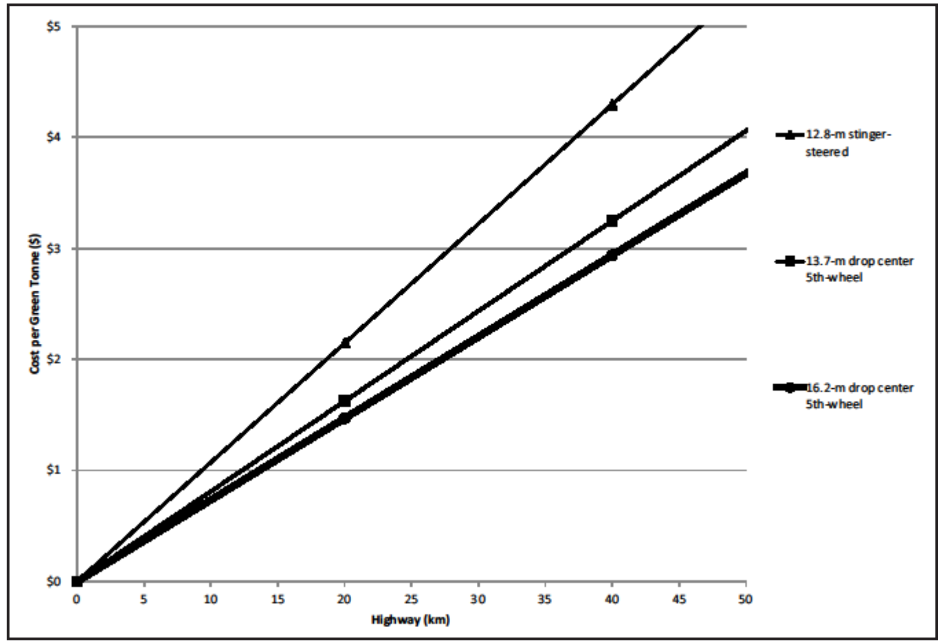

Figure FL-5.38. Comparison of cost per tonne versus highway kilometers when traveled over highway roads. When traveling over highways roads or when traveling on the forest transportation network where no modifications are required for all vehicles, the most economical chip van is the 16.2m drop center 5th-wheel chip van. We assumed each trailer is weight limited.

The breakeven highway distance between the 12.8m stinger-steered chip van and the 13.7m drop center 5th-wheel chip van for the 90 green tonnes of biomass per hectare case as a function of in-forest kilometers (FK) is (operating characteristics from Table FL-5.6 were rounded for ease of illustration):

$$HM= \frac{FKx\left(\frac{2\ x\ \$91}{15 \cdot 29.9} + \frac{0.5 \cdot 3281}{90 \cdot H} - \frac{2 \cdot \$95}{15 \cdot 23.6}\right)}{\left(\frac{2 \cdot \$95}{75 \cdot 23.6} - \frac{2 \cdot \$91}{75 \cdot 29.9}\right)} \qquad [34]$$

Equation 34 is the highway distance (km) needed to be traveled before the 13.7m drop center 5th-wheel chip van becomes economical for a given in-forest hauling distance. The breakeven distance for a harvest area of 50ha between these two vehicles for 2km on forest roads is 17.8 highway km. For distances less than 17.8km, it is more economical to use the 12.8m stinger-steered chip van. For distances greater than 17.8km and less than 179.4km, it is more economical to use the 13.7m drop center 5th-wheel chip van (Figure FL-5.39). A breakeven analysis of an in-forest hauling distance of 15km is shown in Figure FL-5.40.

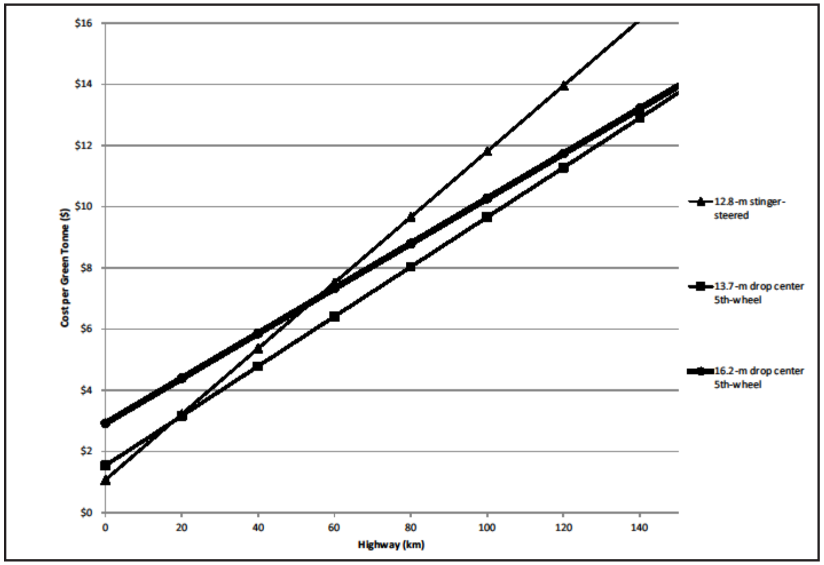

Figure FL-5.39. Comparison of cost per tonne versus highway kilometers when travel is over 2km of forest road. This comparison uses 90 green tonnes per hectare for a 50ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, 17.8km of highway hauling is the breakeven case between a 13.7m drop center 5th-wheel chip van and a 12.8m stinger-steered chip van. The 16.2m drop center 5th-wheel chip van becomes economical over the 13.7m drop center 5th-wheel chip van at 179.4km highway hauling.

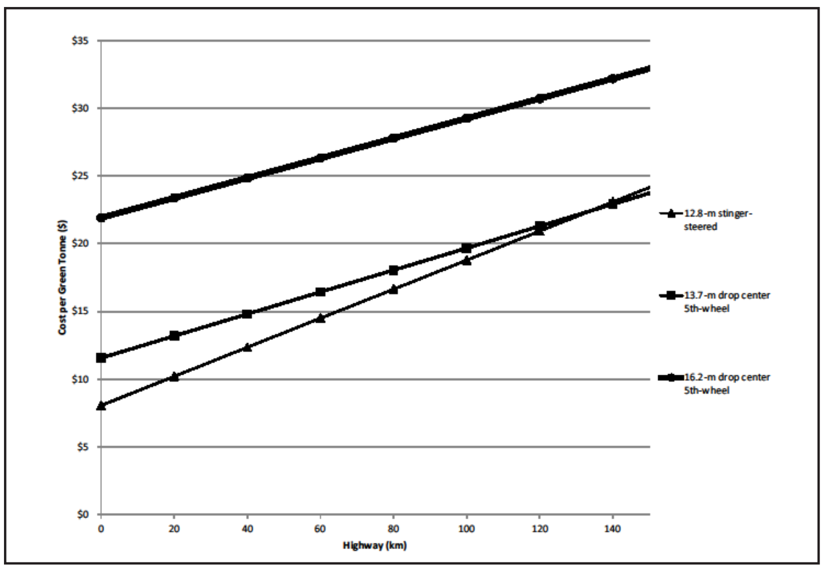

Figure FL-5.40. Comparison of cost per tonne versus highway kilometers when each truck must travel 15km on forest road. This comparison uses 90 green tonnes per hectare for a 50ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van more economical. In this case, 133.8km of highway hauling is the breakeven case between a 13.7m drop center 5th-wheel chip van and a 12.8m stinger-steered chip van.

For the case of removing 45 green tonnes per hectare (such as a thinning operation) on a harvest unit of 50ha and the in-forest, hauling distance was either 2km (Figure FL-5.41) or 15km (Figure FL-5.42). The optimal trucking option would be the 12.8m stinger-steered chip van for highway hauling distances less than 45.7km when hauling on 2km of forest road and 342.6km when hauling on 15km of forest road. As volume removed is reduced, the use of road modifications to allow larger vehicle access tends to increase transportation cost per ton.

From the single harvest unit case, it is apparent that modifying the transportation network is not always the economical option. However, in the McDonald Forest transportation network example, it was cost efficient to modify the network to allow larger vehicles access. By grouping several biomass harvest units in close vicinity, the larger transport volume justifies a greater investment and makes a larger chip van economical.

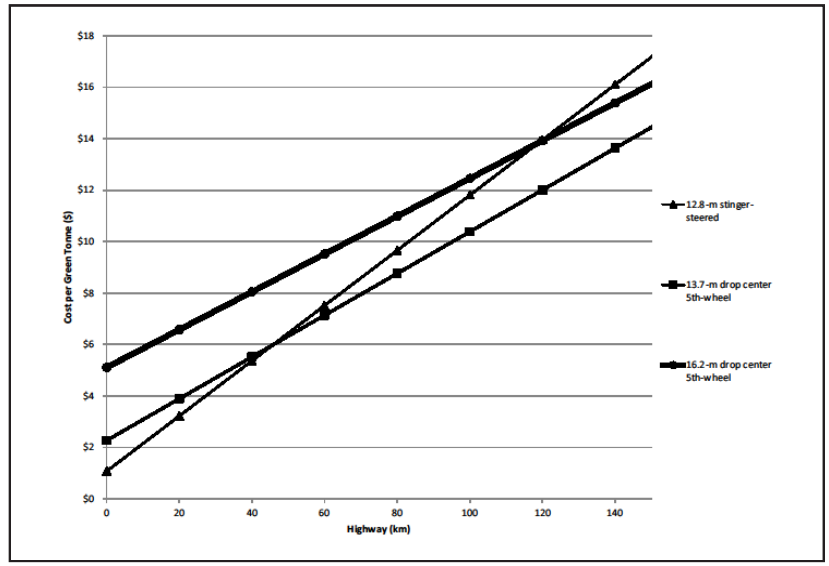

Figure FL-5.41. Comparison of cost per tonne versus highway kilometers when travel of 2km of forest road. This comparison uses 45 green tonnes per hectare for a 50ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, 45.7km of highway hauling is the breakeven case between a 13.7m drop center 5th-wheel chip van and a 12.8m stinger-steered chip van.

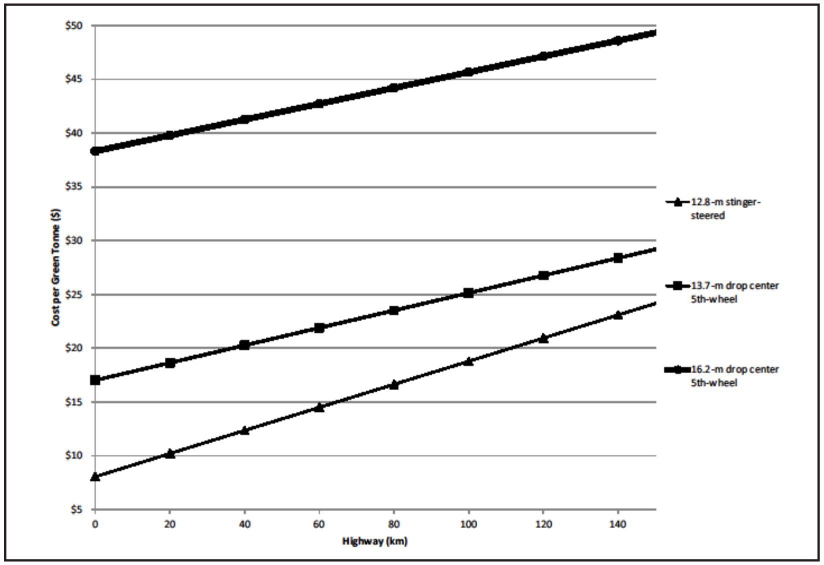

Figure FL-5.42. Comparison of cost per tonne versus highway kilometers when traveled over 15km of forest road. This comparison uses 45 green tonnes per hectare for a 50ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, the 12.8m stinger-steered chip van is the most economical.

5.3. Summary

Unlike the primary log market, roads were not built to extract forest residues and the limited value of these products will usually not support widespread reconstruction of the forest network. However, strategic investments in the existing road network: some temporary, some permanent may be justified. Decision support for temporary activities such as filling ditches and changing road cross slopes to enable large vehicle access has not been available in the literature. When these ideas were applied to schedule multiple biomass operations over a common road network, the ACO heuristic obtained an optimal solution to a small problem; and when applied to a more realistic problem, quickly provided a solution. As transport volume increases, more could be spent on road modifications to allow larger truck capacity access. Being able to modify the forest transportation network to accommodate larger trucks access could greatly reduce biomass hauling costs. Decisions for isolated biomass operations depend on road modification cost, transport volume, and transport costs on forest and highway roads. Breakeven analysis can be used to determine the optimal vehicle type.

6. Conclusions and Future Work

A number of truck and trailer configurations exist for transporting biomass (Section 2). Truck transport efficiency is often maximized by improving large trailer access to the forest. This can be done by improving the mechanical ability of the truck and trailer to access the forest (Section 3 and 4), by temporarily or permanently improving the road system so the truck and large trailer can access the forest (Section 5), or by shuttling the forest residues to a point where large trailers have access and comminution operations can be done at larger scale. Existing biomass operations in the Pacific Northwest use the full range of strategies. At one end of the spectrum, large highway trailers are taken to every forest landing, at the other end of the spectrum, large highway trailers are never taken to the forest landing, but all forest residues are moved to a central location before comminution. The development of the rear-steer trailer coupled with a 6x6 truck-tractor improves road access by reducing off-tracking, increasing the ease of backing up, and improves both unloaded and loaded gradeability. The economic efficiency of this system, under a range of biomass and road network scenarios, is still being evaluated using data collected during the NARA project and will be submitted for peer review in 2017.

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