# Effect of High Speed Blowing on the Bulk Density of Ground Residues

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## Abstract

Transportation costs of ground forest residues can be reduced by increasing the dry wood bulk density per trailer per trip. Increasing the dry wood bulk density can be achieved by compacting the material into the trailer after it is processed by a grinder. However, increasing load density is often difficult to achieve in conventional conveyor-fed, gravity drop loading methods. The effect of high speed blowing during loading of low moisture wood grindings on the final bulk density was analyzed for two feedstock piece sizes, branches-and-tops and pulpwood. A structured fully randomized field test was implemented with two factors: loading method (high speed blowing and conveyor fed) and bit type (carbide hammer bits and knife-edge bits). The high speed blowing of grindings was made using a blower system to pack the material into the trailer during loading. The resulting bulk density using high speed blowing was compared against the results obtained from the conventional conveyor-fed (gravity drop) loading. The high speed blowing method produced a significant increase in bulk density ranging between 24 and 35 percent more than the conventional conveyor-fed loading. In terms of grinding configuration, knife-edge bits produced a higher bulk density (9%) compared with carbide hammer bits but only for the pulpwood piece size class. The use of high speed blowing during loading was the most powerful factor impacting truckload bulk density in these trials and demonstrated promising results that can lead to significantly lower transportation costs when processing low moisture content harvest residues.

Transportation by truck–trailer is a large portion of the total delivered cost of comminuted forest harvest residues, and the load quantity is dependent on the moisture content and dry bulk density of the residues. Dry bulk density is the mass of dry material in a unit of volume, and as long as the truck is below legal weight limits, increasing dry bulk density will allow an increase in dry weight carried per truckload, reducing unit transportation costs. Dry bulk density is the dry weight of the wood per unit load volume (Briggs 1994). It is affected by the comminution system, trailer loading method, particle size distribution, and the specific gravity of the processed biomass, which for residues is typically a mixture of wood, bark, dust, and needles (Hakkila 1989). In this article the effect of the loading method on the bulk density is analyzed.

Commonly, grinders dump the material into the truck through a discharge conveyor. After leaving the conveyor, grindings fall into the truck by gravity. Alternatively, the comminuted material can be accelerated and loaded into the trailer horizontally or vertically using a blower (Fig. 1). The difference between these two loading methods is related to the speed of the particles when loading. In a typical conveyor-fed method, particles are accelerated by the force of gravity only. In a blower loading system, the particles are mechanically accelerated at specific speeds, and therefore each particle contains more kinetic energy that tends to increase the particle settlement. Many commercial chippers have high speed fans or chip accelerators to force the chips into the trailers (Bruks 2013, Morbark 2013). Horizontally blown chips have been tested in the pulp and paper industry with good results in increasing the payload; however, the longer the trailer, the more difficult to pack the chips,

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*Figure 1.—(a) Conveyor-fed loading method into a chip van in a grinding operation; (b) horizontal blowing of wood chips into trailers.*

especially in the front of the container (Thompson et al. 2012). The use of pneumatic blowers is also common when loading railcars for train transportation (Adler et al. 1978). In grinding operations, horizontal blowing has been tested to load trailers by adapting centrifuge blower devices to the grinder (Rawlings et al. 2004). Prior work from Uuscaara and Vekasalo (as cited in Hakkila 1989) has also been done in testing density comparing different loading methods. Although extensive research was found in the horizontal blowing of chips, few studies were found that applied directly to grinding operations, and no research was found in relation to high speed blowing of grindings in a vertical orientation during loading. Grindings differ from chips in being less uniform in terms of particle size distribution, and they usually have a lower bulk density compared with chips (Smith et al. 2012). Grindings usually have a higher proportion of bark and contaminants compared with chips because chipping most often takes place in log-like material that has been processed by delimbers that remove a percentage of the bark. Tests on pulp chips have usually been done at higher moisture contents for the pulpwood market (~50%, wet basis). Here the interest is in lower moisture content material, both to improve transport efficiency and to improve energy value for combustion. Moisture management strategies to improve forest harvest residue values by reducing moisture content have been proposed by Acuna et al. (2012) and Rogers (1981).

In the United States, forest products including forest biomass are predominantly transported using trucks (Angus-Hankin et al. 1995, Forest Resources Association 2006, Schroeder et al. 2007). Low bulk density of processed woody residues often results in a lower utilization of the truck legal load weight capacity (Thompson et al. 2012). Truck capacity can be measured in terms of volume and weight of the trailer (or trailers in double trailer configurations). A truck limited by weight indicates that the maximum allowable legal weight of the truck has been reached. The maximum legal weight capacity is measured as a function of the number and distance between axles and the specific road regulations. A truck is limited by volume when the volumetric capacity of the trailer is reached before reaching the legal weight limit. In such a case, the truck is carrying less than an allowable weight load, and if bulk density could be increased, transportation costs would be reduced. Volume-limited trailer condition is often characterized by transporting dry material that is lower than approximately 35 percent moisture content wet basis. In conveyor-fed loading, the material may not be well packed in the trailer (Fig. 2), and therefore the truck becomes volume limited (Schroeder et al. 2007). Various methods have been explored to increase bulk density. McDonald et al. (1994) summarize mechanical compression and vibration methods. In this article we explore both the effect of near-vertical high speed blowing during loading on bulk density and the interaction of grinder bit configuration and piece size.

In the US Pacific Northwest, harvest forest residues are typically processed using horizontal grinders that reduce the size of the harvest residues by hammering them against an anvil until the particles are reduced to pass through peripheral exit screens. Grinders are favored over chippers because chippers have frequent downtimes in order to replace dull knives contaminated with forest residues (with soil particles), which results in reduced productivity (Ryans 2009, Peterson Pacific Corp. 2013). The comminuted material is then loaded into trailers and transported to a bioenergy conversion facility. The hammering–cutting process is performed by bits attached to a cutting rotor. Carbide-coated hammer bits have relatively blunt edges that are highly abrasive and tend to hammer shred the material. Knife-edge bits tend to cut shred the residue using the sharp edge of the bit. Carbide hammer bits tend to produce less

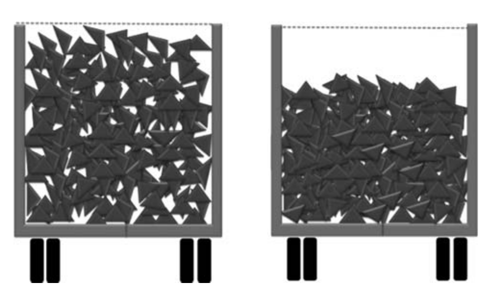

*Figure 2.—Diagram illustrating the potential increase in truck volumetric capacity by increasing bulk density of the comminuted material. As long as the material is dry enough such that the truck is not at legal weight limit, more material can be added to the more compacted load.*

dense material compared with knife-edge bits, but they are less susceptible to contaminants (Hurt 2012).

The main objective of this study was to assess the effect on the bulk density of low moisture content grindings by high speed blowing in a near-vertical direction compared with the usual conveyor-fed trailer loading method. We were also interested in (1) estimating the combined effect of feed piece size and loading method on bulk density and (2) estimating the influence of bit type and loading method on bulk density. This research was based on a controlled experiment that allowed us to isolate the effects of the high speed blowing loading method on bulk density. Our aim is to increase the understanding of comminution and transportation processes in order to evaluate strategies to decrease costs of processing and transport of low moisture forest harvest residues. Biomass from forest residues is a low value product, and therefore any decrease in cost will help to improve cost efficiency and contribute to the long-term success of this relatively new supply chain.

## Materials and Methods

A total of 150 green metric tons of Douglas-fir (*Pseudotsuga menziesii*) harvest residues were transported from an active forest operation (44°11′21″N, 122°59′15″W) to a pulp–paper facility located in Springfield, Oregon (44°3′7″N, 122°57′7″W). The primary objective of the timber harvesting was the extraction of sawlogs for export markets. During these logging operations, no pulpwood had been transported from the harvest unit in part because of the low demand and imports affecting North America in recent years (United Nations Economic Commission for Europe–Food and Agriculture Organization of the United Nations 2012). At the pulp–paper facility, the harvest residues were sorted into two feedstock size classes. The harvest residue material class that is commonly available in typical forest biomass operations consisting of branches and tree tops was separated from the total residue collected. This residue had an average diameter of 6.3 cm ($\sigma$ = 0.77 cm), and an average length of 1 m. This size class was called ‘‘branches-and-tops.’’ The remaining residue was composed of small logs with a diameter ranging from 10 to 30 cm ($\sigma$ = 6.5 cm) with an average length ranging from 1.2 to 4.27 m. In high-demand pulpwood markets this would be considered suitable material for chipping. This residue size class was called ‘‘pulpwood.’’

The test was performed during August and September 2013 and took 10 days to complete. The material was comminuted using a Peterson 4710B (570 kW) horizontal grinder (Peterson Pacific Corp. 2012) equipped with a 20-bit cutting rotor. Hexagon-type screens were used consisting of two grates with an opening size of 7.61 cm, followed by two grates with an opening size of 10.16 cm each. This configuration was selected because it is commonly used in current forest residue harvesting operations in the Pacific Northwest and it follows recommendations made by the manufacturer of the equipment to maintain productivity while decreasing the proportion of overlength pieces (Peterson Pacific Corp. 2013). Two types of bits were tested in three different configurations: (1) carbide hammer bits; (2) knife-edge bits; and (3) combo bits, which consisted of 12 knife-edge bits in the center of the cutting rotor and 8 carbide hammer bits placed in the outer edge of the cutting rotor.

Harvest residues were loaded into the grinder using a John Deere 200 LC track-mounted loader (104 kW). The high speed near-vertical blowing of the grindings was tested using a Peterson BT-40 blower truck equipped with a live floor and a blower system capable of blowing the material at a speed of 54.4 m/s at 2,700 blower rpm (with a discharge hose diameter of 15.2 cm). The blower had a theoretical output of 46 $m^3$/h. Material processed through the horizontal grinder was conveyor fed into the blower truck. The material in the blower truck was then blown from the blower truck by manually holding the discharge hose

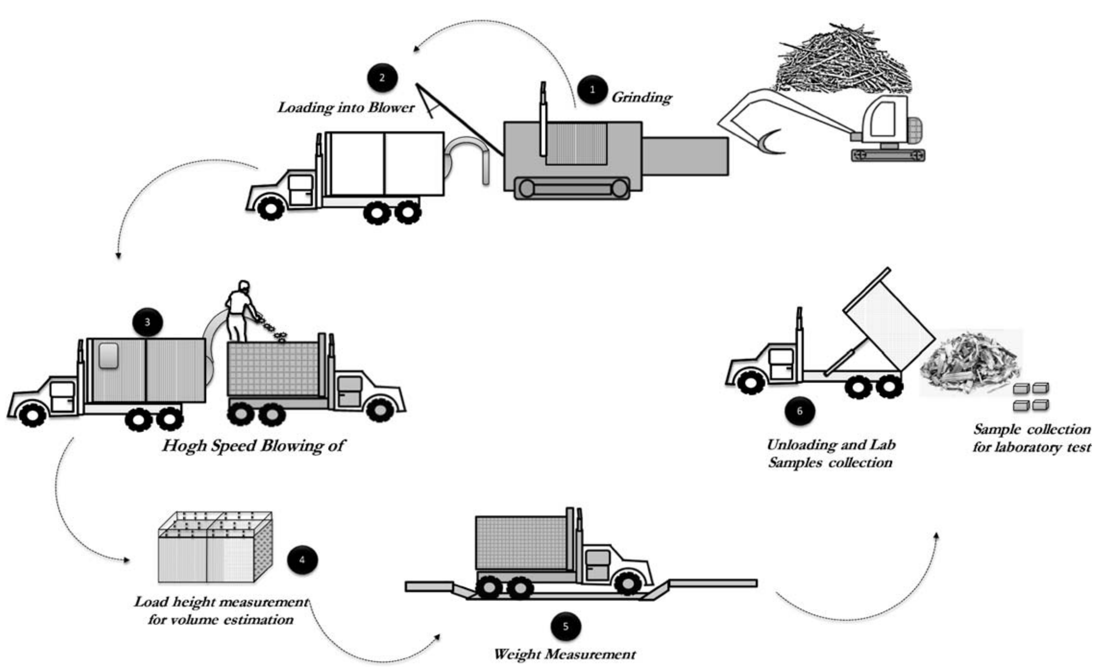


*Figure 3.—High speed blowing test procedure.*

a) b)

*Figure 4.—(a) Near-vertical high speed blowing of grindings during truck loading; (b) conveyor-fed truck loading.*

directly into a dump truck at an approximately vertical angle (Fig. 3). The dump truck was equipped with a rectangular bin with a capacity of 11.7 $m^3$ divided in two compartments of 5.8 $m^3$ (back) and 5.9 $m^3$ (front).

Bulk density was measured by weighing the truck on a scale. Truck empty weight was recorded at the beginning of each testing day or if the truck was refueled during the day. The grindings volume was estimated by measuring the height of the load in systematic sample points located 50 cm apart. An average height was derived and the material volume was calculated based on the width and the length of the rectangular bin.

The crew was composed of a truck driver who operated the dump truck, a blower-truck operator who manually directed the blower hose vertically into the dump truck, one person in charge of the excavator loader operation, and a grinder operator who was in charge of the grinding process and of recording the field data.

In the conveyor-fed loading tests, the material was conveyed and dumped directly from the horizontal grinder into the dump truck, as typically occurs when loading chip vans in the field. A shroud was used to control the grindings flow and to direct fine particles under windy afternoon conditions. Bulk density was measured in the same way as it was during the high speed blowing experiments. The different loading methods are shown in Figure 4.

A fully randomized test was done with two factors: (1) bit type with three levels, carbide hammer, knife-edge, and combo bits; and (2) loading method with two levels, high speed blowing and conveyor fed (gravity drop). In total, six different treatments with four replications per treatment were tested. The randomized treatments and replications are shown in Table 1. The randomized treatments were applied to the two feed size classes corresponding to the branches-and-tops and pulpwood residue. At each trial, an average of 1.3 metric tons of branches and tops and 2.7 metric tons of pulpwood residues were processed. The amount of processed material in each residue type varied because a limited amount of branches and tops was found after sorting, but the experimental design consisting of four replications per treatment was desired to favor the robustness of the statistical model. Processed material from branches and tops was loaded into the back compartment of the dump truck, and pulpwood residue was loaded in both front and back compartments.

After each trial a sample of approximately 36 liters was taken and transported for testing in the laboratory. Laboratory tests included moisture content determination adapted from the ASTM E871-82 standard (ASTM International 2006) and particle size distribution. The moisture content of each sample was used to calculate the ovendry weights for the bulk density. The basic density of the grindings was also calculated following standard ASTM D2395 (ASTM International 2008). The basic density allowed us to calculate the solid fraction using equation 1 from Hakkila (1989). The solid fraction is the number of solid wood cubic meters that will produce a cubic meter of grindings. The basic density of the grindings provided information to assess whether the differences in bulk density were due to variances in wood basic density between samples rather than other factors. Variability in basic density can occur as a result of locations within a tree, between trees, and between species.

$$Sf = \frac{Bk(100 - Mc)}{100\rho} \qquad (1)$$

where

$Sf$ = solid fraction,

*Table 1.—Randomized treatments of bit type and loading method distributed in four replications.*

| Replication 1 | Replication 2 | Replication 3 | Replication 4 |
|---|---|---|---|
| Knife-edge/blower | Combo/conveyor | Carbide/blower | Combo/blower |
| Combo/conveyor | Carbide/conveyor | Knife-edge/conveyor | Knife-edge/blower |
| Combo/blower | Combo/blower | Knife-edge/blower | Knife-edge/conveyor |
| Knife-edge/conveyor | Knife-edge/blower | Carbide/conveyor | Carbide/conveyor |
| Carbide/blower | Carbide/blower | Combo/blower | Combo/conveyor |
| Carbide/conveyor | Knife-edge/conveyor | Combo/conveyor | Carbide/blower |

*Table 2.—Two-way ANOVA results for the bit type and loading method effect on bulk density.*[a]

| Source | df | Type III SS | *P* value |
|---|---|---|---|
| Bit type | 2 | 154.3 | 0.7870 |
| Loading method | 1 | 14459.5 | <0.0001 |
| Bit type × loading method | 2 | 25.9 | 0.9602 |

[a] ANOVA = analysis of variance; df = degrees of freedom; SS = sum of squares.

$Bk$ = bulk density of the load (kg/m$^3$),

$Mc$ = moisture content of the grindings wet basis (%), and

$\rho$ = basic density of the grindings (kg/m$^3$).

Particle size distribution was measured to investigate the effect of bit type and blowing on the bulk density. Particle size distribution was measured using a 50 by 127-cm Rotex oscillatory screen with two decks with round openings. The opening sizes of the upper and middle decks were 0.95 and 5.08 cm, respectively. An 18-liter sample was poured into the oscillatory screen and divided into three particle sizes: oversized, medium, and fine pieces. Collected fractions were weighed and the percentage of each size calculated. After weighing the fractions, the sample was homogenized again and two more replications were performed. Oversized and medium-sized pieces were further classified into a detailed particle size distribution test consisting of manual separation into four fractions based on the length of the particle: (a) <7.62 cm; (b) 7.62 to 15.24 cm; (c) 15.25 to 30.48 cm; and (d) >30.48 cm. Two replications of the detailed particle size procedure were made. Fine particles were classified using a No. 6 Tyler screen with an opening size of 3.35 mm. The sample was placed on a screener vibrator for 4 minutes, and the percentage of particles that passed the 3.35-mm screen was determined. Two replications of this test were performed, and the average was reported. The fine fraction was of interest because others have reported that it contains a significant proportion of the potential contaminants in the grindings (Zhang et al. 2012).

Forest residues contain bark, foliage, and soil. The percentage of bark and other substances was estimated in order to provide more information about the particle size distribution and bulk density results. The bark and other substances content was estimated by manually isolating needles, bark, rocks, and other contaminants from a 5-liter sample. Bark that was still attached to the wood was removed with a small knife. All bark and other substances content was weighed, and the percentage calculated as a function of the total sample weight.

For the statistical test, a factorial analysis of two factors (bit type and loading method) and one dependent variable (ovendry bulk density) was performed. The two-way analysis of variance (ANOVA) was performed in each size class: branches-and-tops and pulpwood. The normality assumption was checked by visually checking Q–Q plots in conjunction with Shapiro-Wilks tests. The equal variance assumption per treatment was analyzed using side-by-side box plots. This also helped us to check for outliers. Levene's test was performed to support the visual interpretation of box plots in relation to the equal variance assumption. The time correlation of the data was tested because field data were collected on different days in order to evaluate independence. Residuals were plotted for each treatment by time as an independent variable. Multiple comparison tests using Bonferroni's correction were made where appropriate to explain the individual factor significance at each of their levels. Our statistical significance was based on the *P* values. For values close to 0.05, it was concluded that a strong statistical significance occurred. For *P* values around 0.10, it was concluded that moderate but inconclusive statistical significance existed.

An economic analysis was also developed to estimate the potential transportation cost savings of increasing trailer payload through the use of a specific bit type and/or loading method. Transportation costs were obtained from consultation with trucking companies in Oregon and Washington and from direct estimation based on the power needed to overcome air and rolling resistance traveling loaded and unloaded. Costs of $100.1/h traveling unloaded and $121.7/h traveling loaded were used in the cost estimations. Additionally a cost of $37.6/h was used when the truck was not traveling, that is, either loading or unloading. For the truck load capacity, the assumption included a truck (335 kW) equipped with a single drop center trailer with a capacity of 100 m$^3$ and a maximum allowable legal weight (truck and trailer) of 40,823 kg. Cost and average life of carbide hammer and knife-edge bits were obtained directly from the manufacturer of the machinery. The average hourly cost of carbide bits was $4 per productive hour with a life of 150 hours. The knife-edge bit cost $14 per productive hour with an expected life of 50 hours.

## Results

### Branches-and-tops residue size class

The branches-and-tops piece size class had an average moisture content of 17.3 percent ($\sigma = 3.3$), wet basis. Basic density of the grindings was 444 kg/m$^3$. Bark and other substances content were estimated as 15.7 percent ($\sigma = 11.2$). No significant departures from normality or violation of the equal variance assumption or time dependence of the data per treatment were observed. Results from the ANOVA test indicate that vertical high speed blowing had a statistically significant effect on the ovendry bulk density. Bulk density increased between 24.3 to 27.8 percent by loading the truck using vertical high speed blowing

*Table 3.—Effect of loading method and bit type on average ovendry bulk density for branches-and-tops size class residue.*

| Bit type | Average bulk density (kg/m$^3$) High speed blower | Average bulk density (kg/m$^3$) Conveyor-fed | Bulk density difference ± 95% CI (kg/m$^3$) | *P* value | % increase |
|---|---|---|---|---|---|
| Carbide hammer | 238.1 | 191.5 | 46.58 ± 26.48 | 0.001 | 24.32 |
| Combo | 242.5 | 193.5 | 49.03 ± 26.48 | 0.001 | 25.34 |
| Knife-edge | 237.6 | 186.0 | 51.66 ± 26.48 | 0.002 | 27.78 |

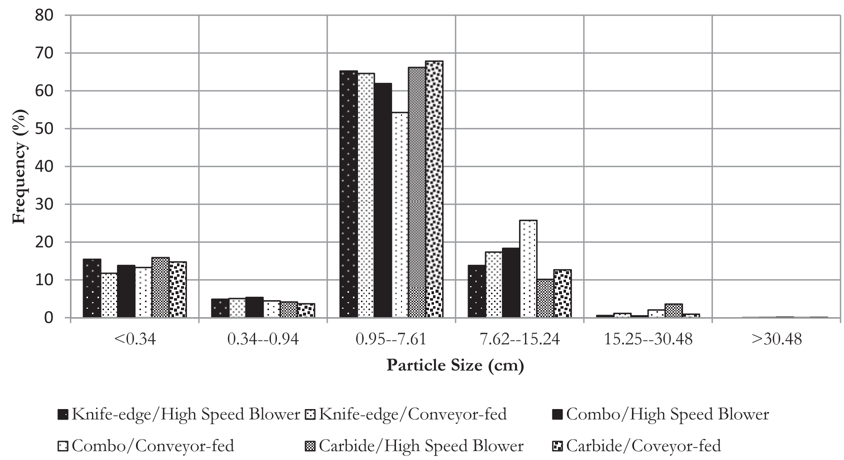


*Figure 5.—Particle size distribution per treatment (bit type loading method) for standard residue size class.*

compared with conveyor-fed loading. The bit type effect resulted in no statistical significance in the ovendry bulk density (Table 2).

Branches and tops processed with knife-edge bits and loaded using the vertical high speed blowing method had an average increase in ovendry bulk density of 51.66 kg/m$^3$ (27.8%) more than the conveyor-fed loading method. For residue processed with a combination of carbide hammer and knife-edge bits, the material blown into the testing truck had an average increase of 49.03 kg/m$^3$ (25.3%). Material processed with carbide hammer bits had an average increase 46.57 (24.3% higher; Table 3). All differences were statistically significant ($P < 0.002$ from a multiple comparison Bonferroni test).

Particle size distribution had a slight increase of fines fraction (<0.34 cm) when the material was blown into the truck compared with the conveyor-fed method (Fig. 5). The proportion of particles greater than 7.61 cm was higher when the material was conveyor fed.

## Pulpwood size class

Grindings processed from the pulpwood size class had an average moisture content of 20.12 percent ($\sigma = 2.44$). Basic density was 401 kg/m$^3$. The percentage of bark and other substances content in this size class was 4.44 percent ($\sigma = 4.68$). The analysis of the assumptions for the ANOVA test did not reveal any violation. Strong evidence was found of the effect of bit type and loading method on the ovendry bulk density; however, the effect of loading method is greater than the effect of bit type. No statistical significance was found in the interaction between the two factors (Table 4).

*Table 4.—Two-way ANOVA results for the bit type and loading method effect on bulk density for pulpwood size class.*[a]

| Source | df | Type III SS | $P$ value |
|---|---|---|---|
| Bit type | 2 | 363.9 | 0.0271 |
| Loading method | 1 | 13998.3 | <0.0001 |
| Bit type × loading method | 2 | 21.2 | 0.7751 |

[a] ANOVA = analysis of variance; df = degrees of freedom; SS = sum of squares.

The effect of the bit type factor is mainly driven by the difference between the bulk density of the grindings processed with knife-edge bits compared with carbide hammer bits for both loading methods. Knife-edge bits produced grindings that were 13.1 kg/m$^3$ denser (8%), on average, compared with carbide hammer bits (Table 5). Statistical differences between the combo configuration and the other two configurations were not significant.

In terms of the loading method, high speed blowing increased the ovendry bulk density between 32.7 and 34.9 percent. Maximum bulk density was achieved using knife-edge bits and decreased for combo and carbide-only bit types

Particle size distribution for the pulpwood size class exhibited a slight increase in the percentage of fines (<0.3 cm) for material processed with knife-edge bits compared with carbide hammer bits. Combo bits produced a greater amount of these fine particles compared with the other two types of bits tested. Slightly more fines were found when the material was blown compared with conveyor fed. A higher percentage of particles larger than 7.61 cm in length were found when processing the residue with combo and carbide bits compared with knife-edge bits. For all treatments with the pulpwood size, fine particles (<0.34 cm in length) constituted 11 percent, particles with a length ranging between 0.34 and 7.61 cm represented 67 percent, and oversized pieces larger than 7.61 cm constituted the remaining 22 percent (Fig. 6).

## Comparison between residue feed size classes

The effect of the treatments between the two material size classes was compared. For all the treatments, the grindings processed from branches-and-tops–type residues had an average bulk density of 47.4 kg/m$^3$ higher (25%) compared with grindings from pulpwood size class. As was shown before, no statistical differences were found in bulk density between the different bit types tested. On the other hand, the loading method showed a significant effect on the bulk density. For all the treatments, the high speed blower loading method increased bulk density 25.8 and 33.7 percent for branches-and-tops and pulpwood size classes, respectively (Fig. 7).

The average solid fraction for each of the treatments in the two size classes was calculated. The solid fraction was

Table 5.—Effect of loading method and bit type on ovendry bulk density for pulpwood size class.

| Bit type | Average bulk density ($kg/m^3$) High speed blower | Conveyor fed | Bulk density difference ± 95% CI ($kg/m^3$) | *P* value | % increase |
|---|---|---|---|---|---|
| Carbide hammer | 182.51 | 137.47 | 45.04 ± 13.44 | <0.0003 | 32.76 |
| Combo | 193.41 | 145.09 | 48.32 ± 13.44 | <0.0002 | 33.30 |
| Knife-edge | 198.89 | 147.34 | 51.55 ± 13.44 | <0.0001 | 34.98 |

based on the moisture content, basic density, and the actual bulk density measured in the field. Values are reported in Table 6. For all the treatments, solid fraction was 13 percent higher for the branches-and-tops size class compared with pulpwood class when high speed blowing was used to load the truck.

## Economic implications in transportation

Based on the results, significant increases in ovendry bulk density can be achieved by vertically blowing the processed material into the truck. The potential increase in payload derived from the transportation cost per ovendry metric ton (odmt) was estimated. Transportation costs are a function of the distance from the harvest unit to the bioenergy conversion facility. Therefore, a sensitivity analysis was performed to illustrate the effect of the blower loading method when one-way distance is varied (Fig. 8). The use of the high speed blowing system on branches-and-tops feedstock can decrease transportation cost from $1.2/odmt (20-km one-way trip) to $8.3/odmt (200-km one-way trip).

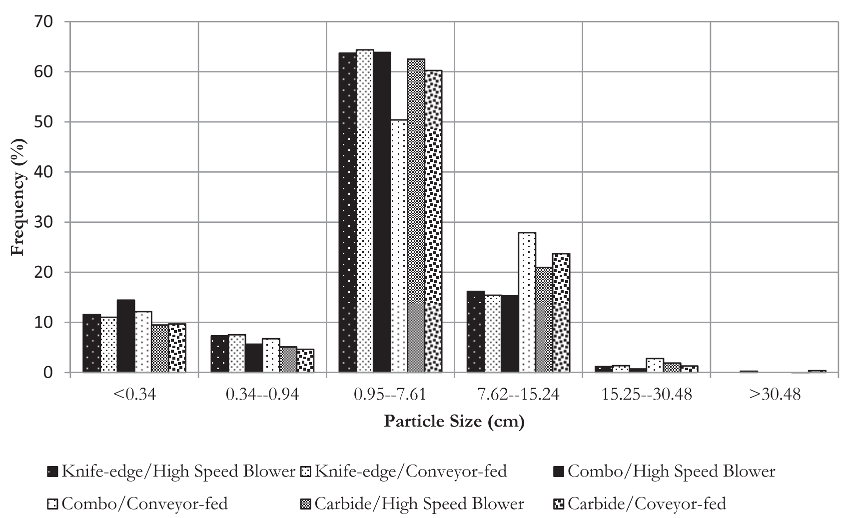


Figure 6.—Particle size distribution for each treatment on pulpwood size class residue.

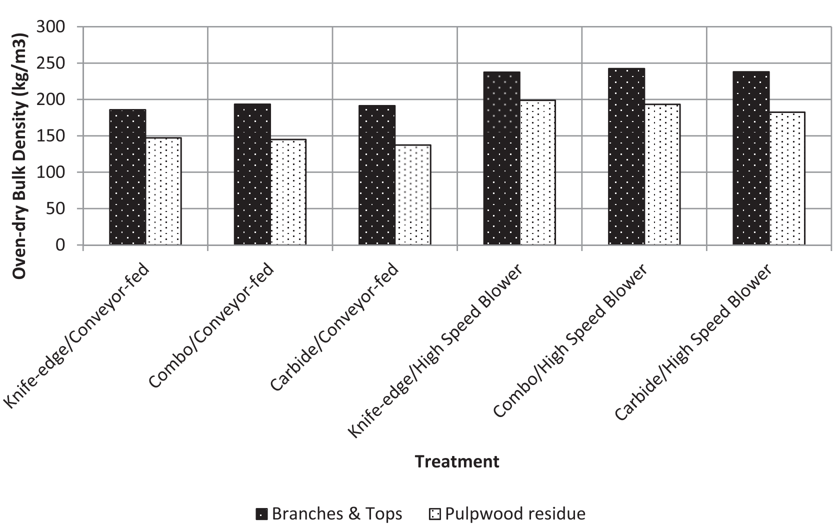


Figure 7.—Effect of the treatment bit type loading method on the bulk density for material processed from branches-and-tops and pulpwood size classes.

*Table 6.—Solid fraction of the different grinding combinations for each treatment.*

| | Solid fraction | | | |
|---|---|---|---|---|
| | Branches-and-tops size class | | Pulpwood size class | |
| Bit type | High speed blower | Conveyor fed | High speed blower | Conveyor fed |
| Carbide hammer | 0.45 | 0.37 | 0.39 | 0.29 |
| Combo | 0.46 | 0.37 | 0.41 | 0.31 |
| Knife-edge | 0.45 | 0.35 | 0.42 | 0.31 |

On pulpwood type material, a combination of knife-edge bits and blower loading produced denser loads compared with the other treatments. The combined effect of high speed blowing and knife-edge bits have the potential to reduce the cost from $2.2/odmt (20-km one-way trip) to $14.7/odmt (200 km from forest to bioenergy facility; Fig. 9).

## Discussion

The use of high speed blowing during loading in a trailer demonstrated promising results in increasing bulk density of the low moisture content grindings and permitted more uniform packing. The uniform packing was achieved during the blowing operation because the operator could manually move the hose side to side to distribute the load uniformly into the trailer. Few problems were found associated with blowing grindings. A few hose obstruction problems were found when processing larger pieces, but in general the testing was not significantly affected by this problem. For the branches-and-tops material, high speed blowing led to significant increases in ovendry bulk density. It would seem to be intuitive that the force with which particulate material impacts the loaded mass would have an effect on the resulting packing of the material, and thus the measured bulk density. For example, conveyor-fed gravity dropping of residues into a 2.5-m-deep trailer might have an average drop height of about 2.5 m. Given acceleration due to gravity of 9.8 m/s, residues would only be traveling at about 7 m/s. Compare this with the exit velocity of the blower tested here, rated at 54 m/s. Because material would begin slowing after discharge from the high speed blower, the terminal velocity before impact appears to be the key factor. Terminal velocity of wood chips and bark in horizontal blowing (an average 7.5-m flight path) has been reported to be in the range of 4.3 to 6.5 m/s (Sturos 1972); however, in near-vertical high speed blowing shorter flight paths can be expected, resulting in a higher impact velocity, producing better packing and higher bulk density.

In terms of feed piece size, the processing of branches-and-tops resulted in higher bulk density compared with pulpwood. This effect is in part due to the higher basic density of grindings from the branches-and-tops size class (10% higher) compared with the pulpwood size class. The lower initial moisture content, higher basic density, and higher bulk density of the branches and tops resulted in a higher solid fraction than for the pulpwood residue. The moisture content of the two materials was different, and friction mechanics may play a role in explaining the effect of moisture content on compressibility, but that was outside the scope of this study. The amount of reaction wood in branches and tops may be the cause of this higher bulk density. Also, the branches-and-tops size class had a higher percentage of bark and other substances. The particle size distribution of bark and other substances content may also explain, in part, the higher bulk density in branches and tops. Bark can be easily broken into fine pieces and also contains soil particles and other contaminants that could cause an increase in the amount of fines. The amount of fines in grindings from the branches-and-tops size class was 14 percent compared with 11 percent of those coming from the pulpwood size class. The proportion of oversized pieces increased when processing pulpwood type residue. The fraction of oversized pieces larger than 7.61 cm increased 4 percent in pulpwood grindings compared with the branches-and-tops size class.

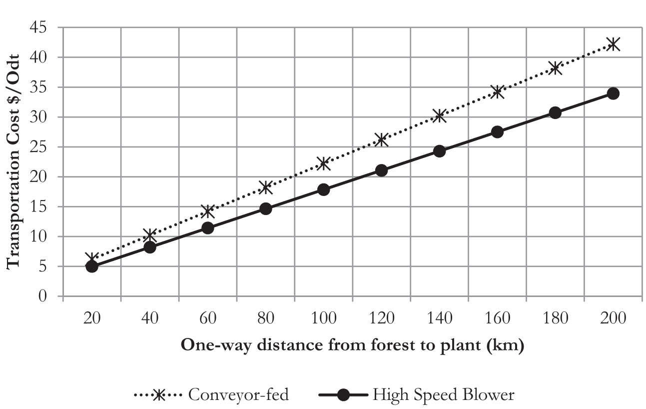


*Figure 8.—Transportation cost for each of the two loading methods on branches-and-tops size class material.*

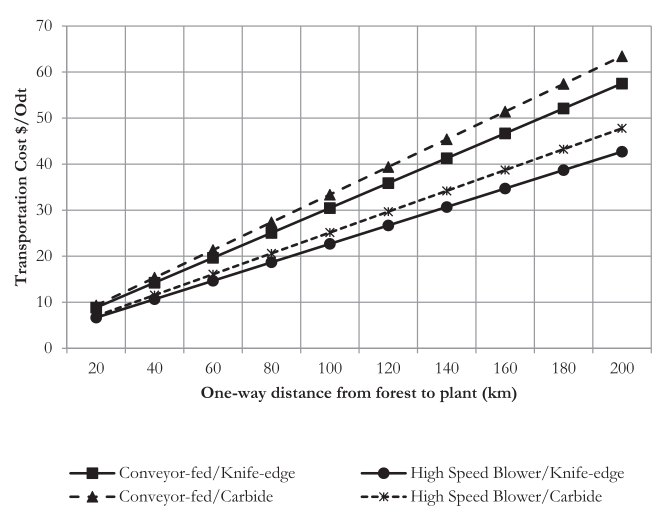


*Figure 9.—Transportation cost for each of the two loading methods on pulpwood size class residue.*

Bit type did not appear to have any effect on increasing bulk density; the small diameter of the material may not have fully exploited the knife-edge bit capabilities. Potentially, the directional feed across the grain when processing branches and tops cannot be properly done due to the different size and characteristics of the material mixture. This is an important conclusion given that bit type has been considered a key factor for affecting bulk density; however, for the study conditions, no significant statistical effect was found.

For the pulpwood size residue, a significant effect of bit type and loading method was found on ovendry bulk density, although the effect of bit type was mainly driven by differences between grindings processed with knife-edge bits compared with carbide hammer bits. Knife-edge bits cut the material instead of just breaking it by brute force. During the crosscutting more fines are produced that may led to increases in bulk density of the load. Additionally, pulpwood compared with branches-and-tops residue is easier to load into the grinder favoring the cut across the grain. A higher ovendry bulk density was achieved using a combination of knife-edge bits and high speed blowing when loading; however, knife-edge bits tend to wear more quickly than carbide hammer bits because they are more susceptible to contaminants. This may increase the grinder downtime and reduce productivity. A productivity analysis must be done to properly test the economic efficiency of this combination.

In terms of transportation, the increase in the amount of material per trailer per trip can lead to potential savings that are proportional to the travel distance. If the demand of forest biomass from harvest residues increases, longer hauling distances could be expected to supply the demand.

## Conclusions

Based on the results of this study, high speed blowing can increase bulk density about 30 percent, suggesting significant potential reductions in transportation costs could be achieved by developing vertical high speed blowers on grinders that can both increase packing by impacting with greater force and also evenly load the trailer. The experiment compared high speed blowing with conveyor-fed loading into a dump truck. In actual operations, the trailer height is up to 2 m higher, so the grindings fall farther and are packed deeper than in the dump truck container; therefore, different bulk densities may be expected when loading truck–trailers. The actual mechanism involved in the increase in bulk density is related to the high velocity of the particles, but this variable was not measured directly. Future studies can test the effect of blower speed on bulk density.

The results of this study indicate that increasing truck capacity by loading with a high speed blower would lead to reduction in transportation costs. However, other factors that could affect the total costs were not part of this study and should be addressed in future work. These include (1) the effect of dense packing on the unloading process at the plant; (2) trade-offs of installing the blower on grinders and providing the mobility to evenly load a trailer; (3) blower power requirements; (4) manpower and operator skills to properly operate the grinder and blower; and (5) equipment costs and potential increases in equipment fuel consumption.

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