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RESEARCH ARTICLE

Truck configurations for efficient transportation of forest biomass: a short literature review

Connor Howitt[1], Mohammad Reza Ghaffariyan[2]

[1] *School of Science, Technology and Engineering, University of the Sunshine Coast, Petrie, Queensland, Australia*
[2] *Forest Industries Research Centre, University of the Sunshine Coast, Locked Bag 4, Maroochydore DC, Queensland*

Corresponding author: Mohammad Reza Ghaffariyan (mghaffar@usc.edu.au; ghafari901@yahoo.com)

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Abstract
This literature review aimed to identify the most efficient truck configurations used to transport forest biomass and the factors that affect their transportation efficiency. The review analysed studies that investigated various truck/trailer configurations for transporting forest biomass. The studies considered factors that influenced biomass transport efficiency such as material bulk density, moisture content, hauling distance, maximum permitted truck weight limits, and payload capacities. Recent literature on forest biomass, truck configuration, and productivity were analysed to determine the efficiency of different truck configurations and their fuel usage and emissions. The study reviewed truck configurations for transporting forest biomass and identified that their transportation efficiency was influenced by variables including material density, moisture content, hauling distance, weight limits, and payload capacities. Larger trucks were generally more efficient due to their higher volume and weight limits, except in situations where road access was difficult. The reporting of fuel consumption and emissions for each configuration was inconsistent across international studies. The information presented in this literature review attempts to summarise the recent knowledge of the biomass industry to inform best practice for efficient and cost-effective transportation of forest biomass.

Keywords
Forest, Biomass, Efficiency, Productivity, Transportation, Truck configuration

Introduction

Forest biomass is a renewable energy source that can provide a carbon-neutral alternative to fossil fuels when used sustainably (Hiloidhari et al., 2019). Studies have projected forests to be a significant source of future bioenergy without exacerbating deforestation (Smeets, Faaij, 2007). Forest-derived biomass can be classified into two types; primary feedstocks removed from forests and secondary feedstocks from forest manufacturing by-products (van Stralen et al., 2016). Primary feedstocks consist of residues from harvesting trees, including stems or whole trees during forest thinning, while secondary feedstocks comprise by-products from processing wood such as bark, chips, and sawdust (Titus et al., 2021). After tree harvesting, forest residues are often available in abundance and are a cost-effective source of biomass for renewable energy (Figueiredo da Silva, Ramos, 2019). However, the dispersed location of these residues within the forest can make the access of certain truck configurations difficult, leading to low transport efficiency and high transportation costs (Figueiredo da Silva, Ramos, 2019).

The transportation process of forest biomass involves the transfer of forest biomass material or harvesting residues from logging sites or sawmills to facilities such as heating plants, pulp plants, or export harbors (Han, Murphy, 2012). The transportation process is complex due to the presence of numerous supply and demand points, a range of truck and trailer configurations, and different types of forest residue characteristics (Han, Murphy, 2012). Moskalik, Gendek (2019) noted that road transportation is the common method of biomass transportation in many countries.

The transportation process of forest biomass materials represents a significant proportion of the overall supply chain costs, up to 40 to 50 percent in some cases (Angus-Hankin et al., 1995; Pan et al., 2007). Cost dependent factors of transport include hauling distance (Pan et al., 2007), load bulk density (Angus-Hankin et al., 1995), and moisture content of delivered materials (Angus-Hankin et al., 1995). Likewise, the transportation process accounts for a significant proportion of the total supply chain emissions, with some studies indicating emissions can be as high as 77% (Kühmaier et al., 2022). For forest biomass to be a sustainable energy source, it is vital to optimise the transportation of biomass (Kühmaier et al., 2022), as greater transport efficiency can lead to a reduction in CO_2 emissions (Kühmaier et al., 2022).

Breaking forest biomass residues into smaller pieces, also known as comminution, can increase material density (Eriksson et al., 2013). Comminution can occur at different locations and stages of the transport process such as the logging site, roadside landing, terminal, or plant (Laitila, 2012; Routa et al. 2016; Wolfsmayr, Rauch, 2014). This process has been studied and found to increase transport efficiency as each truck can carry larger volumes at lower weight, reducing transport cost and CO_2 emissions. (Eriksson et al., 2014; Routa et al., 2016; Wolfsmayr, Rauch, 2014).

The various types of biomass removed from forests, and forest residues have unique characteristics that affect transportation efficiency (Wolfsmayr, Rauch, 2014). The moisture content (MC) of forest biomass is considered one of the largest controllable factors determining the efficiency of transportation (Talbot, Suadicani, 2006), as higher moisture content increases material's mass through water weight, lowering the available volume in transportation (Gendek et al., 2018), thus increasing the cost of transportation and reducing efficiency (Wolfsmayr, Rauch, 2014). On the contrary the reduction of moisture content in biomass materials using natural air drying generally reduces transportation costs as more pure material without excess water weight is delivered per truck load (Murphy et al., 2012). If moisture content of biomass materials is not accounted for or unknown it can result in the weight limit of a truck being accidentally exceeded (Schroeder et al., 2007), particularly during seasonal weather changes (Sosa et al., 2015).

In the last two decades, multiple studies have been conducted on the performance and productivity of timber harvesting machines and processes (Kewilaa, Tehupeiory, 2018; Ghaffariyan, 2010, 2019; Ghaffariyan et al., 2017; Akay et al. 2020; Bergström, Di Fulvio, 2019), however, the transportation efficiency of biomass has not been extensively studied in Australia.

The aim of this study is to conduct a literature review with three goals. Firstly, to identify transport trucks and trailers used for forest biomass and their specific configurations. Secondly, to analyse their performance efficiency. Lastly, to gather information on their fuel consumption and corresponding emissions. The results of the literature review can be used by the Australian forestry industry and the wider community of forest engineering. Reviewing the literature will provide valuable insights into the current knowledge on the most efficient truck configurations for transporting forest biomass.

Methods

For this research 30 literatures published within the last 10 years in the English language were found through online journal articles by searching electronic databases such as Google Scholar, and Scopus. The following keywords were used for the electronic search: forest biomass, truck configuration, productivity, efficiency, and time study. The articles for review were classified into geographical areas based on where the research was conducted. The literature was analysed to find information regarding the productivity of various truck configurations, and their corresponding fuel usage and emissions.

Work efficiency is defined using a time study method where transport time (including productive and delay times) and work output (volume or weight of transported wood) are measured (Griliches, 1998, cited in Heinimann, 2021; Magagnotti et al., 2012). Different factors can impact the productivity of a truck including transport distance, load weight, road types, truck configurations (Brown, 2021; Brown, 2008; Acuna et al., 2012; Sondip et al., 1997)

Results

North America

The study by Zamora-Cristales et al. (2015) in the Pacific North-West USA, aimed to create an optimisation model that could identify cost-effective processing and transportation of forest biomass. One of these parameters to achieve this aim was determining the most cost-effective and productive truck configurations for biomass transportation. Specific circumstances such as forest road access and hauling capacity of different truck trailer configurations were considered.

The truck trailer configurations investigated were double trailers, drop-centre chip vans, stinger steer, and rear-steer axle trailers, and three types of short trucks: bin trucks, hook-lift trucks, and end-dump trucks.

The stinger steer and rear-steer axle trailer configurations had larger hauling capacities than the drop-centre chip vans but were more expensive. The short trucks had a smaller hauling capacity than drop-centre chip vans but were more cost-effective. The most efficient truck configuration for transport varied based on specific characteristics of each area of the forest, the location of the log residue piles, and ease of road access for trucks to these areas. The study concluded that the larger trailer configurations were more efficient for transport over smaller trailers, except in situations when road access was difficult, then the double 9.75 meter trailer configuration was a more efficient option. This was due to the fact that being able to transport larger loads per each turn reduced the required transport time in each working cycle.

Europe

Finland

The Finnish study by Laitila et al. (2016) aimed to determine the most efficient and cost-effective truck type for transporting forest chips and industry by-products. The study analysed four truck configurations; a 48-tonne semitrailer, a 60-tonne conventional truck-trailer, a 76-tonne truck-trailer, and a 69-tonne modern truck-trailer equipped with an Electronic Trailer Steering System (ETS).

The transportation of forest chips was carried out using the 48-tonne semitrailer, 60-tonne traditional truck-trailer, and the 69-tonne modern truck-trailer. While the forest industry by-products and ground stumps were transported using a 60-tonne traditional truck-trailer, a standard 69-tonne truck-trailer, and a 76-tonne truck-trailer. The fuel consumption recorded for each truck configuration can be seen in Table 1.

Table 1. Fuel consumption in litres consumed per 100km for each truck configuration (Laitila et al., 2016)

Truck configuration	48 tonne semitrailers	60 tonne truck trailers	69 tonne ETS truck trailer	76 tonne truck trailers
Fuel consumption (litres/100 km)	45	55	62	66

The study showed that transport efficiency of each truck type was affected by the filling rate, which, in turn, was influenced by the bulk density and maximum permitted weight limits of the biomass material being transported. The 48-tonne semitrailer was the most efficient option for whole-tree chips, with a filling rate of 100%, and for wood chips produced from harvesting residues over short distances, with a loading capacity of 93%. The modern 69-tonne ETS truck-trailer was the most efficient option for transporting logging residue chips over longer distances, with a loading capacity of 74%. The 76-tonne truck-trailer was the most practical choice for heavier forest by-products, with a filling rate of 96% for Scots pine sawmill chips and 91% for birch bark. The study concluded that the most efficient truck-trailer type depended on the material being transported, transport distance, and payload capacity.

Ireland

Another study conducted by Sosa et al. (2015) in Ireland aimed to optimise the transport cost and efficiency of biomass delivery to the Edenderry Power plant using a linear programming tool. The study considered two supply chain scenarios and used moisture content and truck configurations (5-axle and 6-axle) as key factors for optimisation. The results showed that 6-axle trucks could carry an additional 4 tons of biomass, leading to 14.8% fewer truckloads, 14.8% fewer travelled kilometres, and 12.3% less transport cost compared to 5-axle trucks. The study also examined the legal gross vehicle weight (GVW) of the 5-axle and 6-axle trucks. This revealed that fully loaded trucks carrying biomass with low MC could not reach the maximum legal weight limit due to volume constraints, while those carrying biomass with high MC risked exceeding legal weight limits. The study therefore suggested that the most efficient truck payloads are materials at 45% MC for 5-axle trucks and 54% for 6-axle trucks.

Portugal

Figueiredo da Silva, Ramos (2019) conducted a study to determine the transportation efficiency of eucalyptus harvesting residues in Portugal, considering factors such as truck configuration, biomass physical characteristics, and payload. The study compared scenarios where harvesting residues were transported directly without comminution, transported directly after comminution as shredded biomass. The study found that the most efficient truck type depended on the specific circumstances. Direct transport of non-shredded harvesting residues with a 70 m^3 semi-trailer did not utilise the maximum load capacity of the truck at 65% of maximum payload with a mean moisture content (MC) of 42%. While direct transport of shredded harvesting residues with a mean MC of 43%, with the 77 m^3 semi-trailer achieved 76% of the maximum payload. The 90 m^3 semi-trailer achieved 80% of the maximum payload. The larger semi-trailer (90 m^3) was therefore preferable in terms of transport efficiency as it could maximise payload capacity, thus minimising transportation costs, though its access to certain forest terrains was restricted. Figueiredo da Silva, Ramos (2019) also concluded that the current transportation processes in Portugal results in underutilised truckload capacity when MC is below 50%.

Asia/Oceania

Australia

In a study by Strandgard et al. (2021) comparing truck configurations for transporting residues of *Pinus Radiata* plantations in Australia. This research project investigated five different truck configurations. They were 6-axle semi-trailers, 9-axle B-doubles, high volumetric (HV) capacity versions of these two trailers, and 11-axle pocket road trains. Two scenarios were modelled: one with no roadside drying or storage of biomass, and the other involving storage and drying of biomass at the roadside. Here we can add storage period, MC% and its range for each scenario applying natural air drying.

The study found that all truck configurations, except the semi HV and B-double HV, were limited by their volumetric capacity before weight capacity in Scenario 1. In Scenario 2, all truck configurations were volume-limited before they reached weight capacity. The 11-axle pocket road trains (PRT) truck was identified as the most efficient configuration due to its high load weight and volumetric capacities resulting in fewer required truck trips than the other configurations (Table 2).

Table 2. Truck trips required to transport harvesting residues quantities for each truck configuration and scenario (Strandgard et al. 2021)

	Semi	Semi HV	B-double	B-Double HV	PRT
Scenario 1	1377	1293	860	826	738
Scenario 2	1180	1079	672	504	490

Though the high-volume variants of the semi-trailer and B-double truck configurations were also able to transport a considerably greater weight of harvesting residue chips per load in both scenarios than the non-HV configurations (Table 2). However, the benefits of the high-volume semi-trailer and B-double variants were not significant over non-HV variants unless the scenario with roadside storage and drying was utilised.

Conclusion

This review identified truck configurations used in the literature to transport forest biomass and identify the variables that affect their transportation efficiency. Common variables found were material bulk density, moisture content, hauling distance, maximum permitted truck weight limits and payload capacities.

Several of the reviewed studies (Figueiredo da Silva, Ramos, 2019; Zamora-Cristales et al., 2015; Strandgard et al., 2021) suggested that larger truck/trailer configurations were generally more efficient for transport over smaller configurations due to their higher volume and weight limits, except in situations where road access was difficult due to their size. The larger truck volumes increased truck payload capacity and thus required fewer truck trips to deliver forest biomass.

Previous research (Sosa et al., 2015; Strandgard et al., 2021; Laitila et al., 2016) identified several situations where certain truck configurations had advantages or disadvantages over others depending on the situation, or the material transported. The conclusion drawn from them indicates that selecting the most efficient truck configuration for transporting forest biomass is complex and ultimately varies depending on the specific circumstances.

Despite the comprehensive search strategy for literature, some specific parameters, such as emissions or fuel consumption of each truck configuration, or the use of time studies, were not always reported consistently across studies. Therefore, future studies should aim to report parameters such as fuel consumption and emissions for each truck configuration, enabling more accurate and comprehensive comparisons between truck configurations. Nonetheless, the summaries obtained from the reviewed literature offer valuable insights into the current knowledge on efficient truck configurations for transporting forest biomass.

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