

Energetic efficiency of forest transport as a tool for sustainable management of the activity

ABSTRACT

Background: The global interest in reducing fossil fuel consumption and greenhouse gas emissions is not recent. Under this light, this study aimed to correlate the energetic efficiency of wood transport, using the specific fuel consumption, with the variables wood drying time, truck power, fuel consumption and transport distance, in addition to adjusting equations for estimating energetic efficiency of the activity.

Study Design and Methodology: From a database of a forest transport company operating in the State of Minas Gerais, Brazil, the results of 1,387 trips were compiled, with an average distance of 110 km, using forest bi-train and tri-train trucks, with which simulations were carried out considering the effect of wood drying time in the field, fuel consumption, truck power and transport distance on the energetic efficiency of wood transport.

Results: The results showed the existence of a strong negative correlation between the drying time of the wood in the field, the fuel consumption of the trucks and the increase in power in them and the energetic efficiency of the wood transport. Moreover, every 10 days of drying the wood in the field there is, on average, a 2.0% reduction in the moisture content of the wood. and, as a consequence, an improvement of 2.8% in the energetic efficiency of wood transport, keeping the other conditions constant. Additionally, it was verified that a reduction of around 10% in fuel consumption is capable of providing an improvement of around 9.0% in the energetic efficiency of the activity; and that an increase of 20 CV in the power of the trucks represents a possible gain of up to 4.4% in the energetic efficiency of the wood transport activity, keeping all other variables constant.

Conclusion: It is concluded that the search for improvement in the energetic efficiency of the wood transport activity can represent an important tool for a management model based on the principles of sustainability by providing greater efficiency in fuel consumption and its associated benefits, such as the reduction of CO₂ emissions per unit of wood transported.

Keywords: Fuel consumption; wood transport; forest management; atmospheric emissions; sustainability.

1. INTRODUCTION

Starting from the assumption that the global interest in reducing the consumption of fossil fuels and gas emissions for environmental and economic reasons is not recent, the

production chains are also beginning to pay attention to these aspects, especially when extensive use is made of the fuel in some of its stages, such as road forest transport.

In Brazil, the planted tree sector has been an important indicator of economic, social and environmental development in such a way that the sector has become competitive and booming, making it necessary to increase the wood production area and, consequently, transport [1]. The Brazilian forest transport matrix is essentially road [2], as a reflection of the national transport matrix in general, in such a way that a high consumption of fossil fuels is directly associated with this.

The programs that regulate vehicle emissions have served as a measure to certify that vehicle manufacturers work to reduce pollutant emissions and comply with regulated limits. Faced with this need, efforts have brought together vehicle and engine manufacturing companies, together with institutions in the field of fuels, lubricants and components in the search for technologies to optimize fuel consumption and improve the emission levels of new vehicle engine designs [3].

Fuel consumption can be presented as unit of volume per unit of time (liter/h) or unit of volume per distance traveled (km/liter), cases in which the influence of temperature variation is not considered, nor the amount of power generated; although they are the most common forms of management used in forest transport companies.

Another way of presenting fuel consumption is as a unit of mass per unit of time (kg/h); in this form, despite considering the influence of temperature, it also does not consider the power generated. The most technical way of expressing consumption is the unit of mass per unit of power ($\text{g/kW}\cdot\text{h}^{-1}$); this form is known as specific consumption and, due to the fact that it considers mass and power, it can be used to compare engines, tractors and equipment of different sizes and shapes [4].

Thus, the determination of fuel consumption (in liters/h or km/liter) does not seem to be enough to demonstrate the energetic efficiency of the system, as well as to provide subsidies for decision-making regarding the dimensioning of vehicles for transporting wood. Therefore, there is an increasing concern in establishing methodologies that do not compromise the energetic efficiency of the transport system, maximizing it and minimizing polluting gas emissions, mainly, aiming at reducing consumption and fuel costs through a correct decision-making involving the type of truck to be used, mechanical maintenance management programs and forest road maintenance programs, for example.

Thus, this study aimed to correlate the energetic efficiency of wood transport ($\text{g/kW}\cdot\text{h}^{-1}/\text{m}^3$) with the variables wood drying time, truck power, fuel consumption and transport distance, and to adjust equations regression to estimate the energy yield of wood transport, in order to contribute to the sustainable management of the activity.

2. MATERIAL AND METHODS

2.1 Data collection

Data were collected in areas of a forestry company located in the State of Minas Gerais, Brazil, located between the meridians from $42^{\circ}48'00''$ to $43^{\circ}43'00''$ longitude West of Greenwich and the parallels from $16^{\circ}49'00''$ to $17^{\circ}42'00''$ latitude south of the equator. The altitude varies between 600 and 1,100 m.

The region covers areas with average annual rainfall ranging from 750 mm to 1,400 mm. According to the Köppen climate classification, the predominant climate types in the region are Aw - tropical rainy savannah, that is, dry winter and maximum rainfall in summer, and the rainy season occurs between the months of October and March [5] and Cwb - temperate rainy and moderately hot, with a preponderance of rain in mildly hot summers [6].

In the study area, the forests are, in their entirety, cultivated with eucalyptus in stands of hybrid clones (*Eucalyptus urophilla* x *E. grandis*) with an average productivity of 245 m³/ha, in a tall stem regime with a 7-year-old rotation, spacing 3 x 3 m. Harvesting, in turn, is carried out through the system of whole trees (full-tree), a system in which, according to Malinovski et al. [7], the tree is felled and taken to the side of the road or intermediate yard, where it is processed in the form of logs six meters long.

2.2 Wood transportation

The transport of wood from the field to the consumption units was carried out using forestry bi-train and tri-train trucks (Figure 1). The bi-train types have a nominal capacity of 42.4 m³ of wood in logs six meters long, limited to 57 t of total combined gross weight, which, discounting the tare weight of the tractor and implement, represents a maximum capacity of 37 t payload. In turn, the tri-train type have a nominal capacity of 58.5 m³ of wood, limited to 74 t of combined total gross weight which, discounting the tare weight of the tractor and implement, represents a maximum capacity of 51 t of payload. In both cases, all load capacity values are in accordance with the limits established in specific Brazilian legislation.

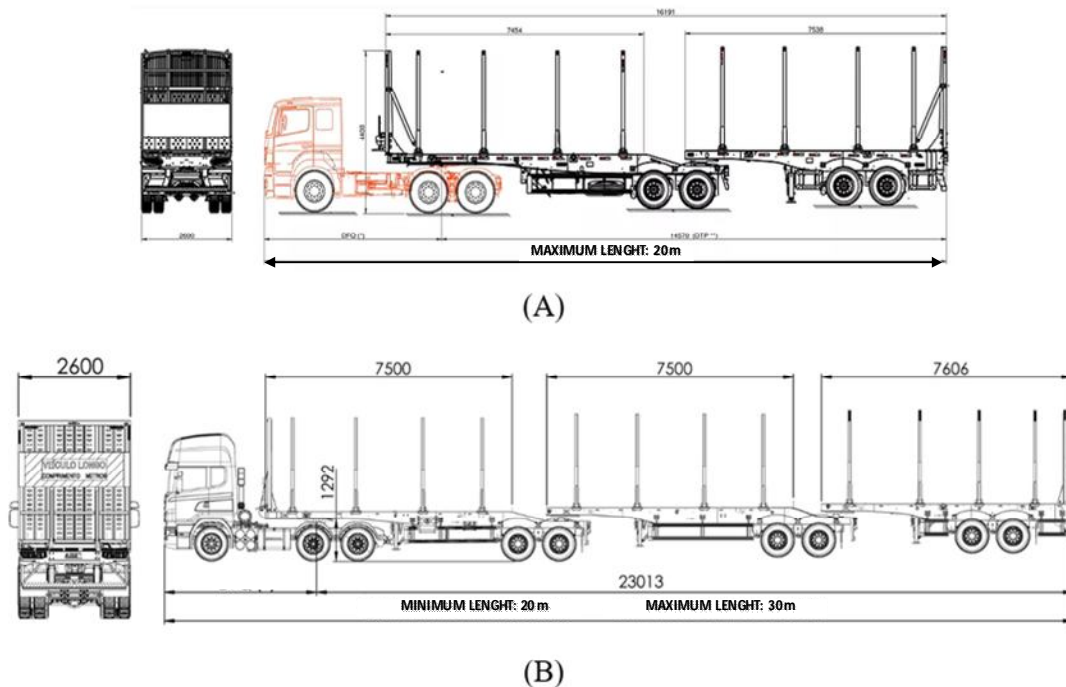


Fig. 1. Bi-train (A) and tri-train (B), sets used to wood transportation.

The wood transport trips of 16 trucks were monitored from January to December 2020, totaling 1,387 round trips. The vehicles had powers ranging from 420 to 540 hp and the following average data per truck were considered: volume of wood (m³) per trip; average fuel consumption (km/l) and average speed of the complete round trip (km/h). Based on these

data, other analyzes were carried out to calculate the energy yield of the wood transport process.

2.3 Determination of wood moisture content

To determine wood moisture after harvesting and processing, during the drying period at the edges of the stands, it was assumed that the daily moisture loss of eucalyptus wood is 0.1288% [8].

The daily wood moisture values were estimated from the time of harvest to 160 days of drying, which is the maximum drying time of wood in the field adopted by charcoal producing companies in the study region. To estimate the values of energy yield from the transport of this wood, intervals of 10 days of drying were considered.

2.4 Determination of energetic efficiency

The energetic efficiency of wood transport was determined from the fuel consumption of the trucks used to transport the wood, considering the variation in the volumes of wood transported after different periods of drying the wood in the field. For this purpose, the energy yield per unit of transported wood (m^3) was calculated, according to Equations 1 and 2, below.

$$EE = \frac{SFC}{P} \quad (\text{Eq.1})$$

where: EE = Energetic efficiency ($g/kW.h-1/m^3$); SFC = Specific fuel consumption ($g/kW.h^{-1}$); P = Productivity (m^3/h).

$$SFC = \frac{FC}{MP} \times FD \quad (\text{Eq. 2})$$

where: FC = Fuel consumption (l/h); MP = Motor power (kw); FD = Fuel density (kg/m^3).

2.5 Statistical analyzes

It was evaluated whether the values found for energy yield are associated with each other and with the values of wood volume after different drying times in the field (m^3/t), truck engine power (CV), fuel consumption (km/l) and transport distance (km , considering round trip). For this, the degree of association was obtained by analyzing the Pearson correlation coefficient matrix (r), using the t test at 5% probability; being considered a strong correlation when $r \geq |0.50|$, medium when $|0.50| > r > |0.30|$ and low when $r \leq |0.30|$, according to Cohen [9]. Analyzes were performed in an Excel environment.

In order to establish a relationship between the energetic efficiency of wood transport (dependent variable, in $g/kW.h-1/m^3$) and having the datasets of wood moisture content, truck engine power, consumption of fuel and transport distance (independent variables), applying nonlinear regression techniques [10], the following model (Eq. 3) was adjusted for each type of truck (bi-train and tri-train):

$$Y = \beta_0 + \frac{\beta_1}{X_1} + \frac{\beta_2}{X_2} + \frac{\beta_3}{X_3} + \beta_4 X_4 + \varepsilon_i \quad (\text{Eq. 3})$$

where: Y = dependent variable; X_1, X_2, X_3 and X_4 = independent variables; $\beta_0, \beta_1, \beta_2, \beta_3$ and β_4 = model parameters; and ε_i = random error.

The adjusted equations were evaluated using the coefficient of determination (R^2), the coefficient of variation (CV%) and the correlation coefficient between the observed and estimated values squared ($Ry\hat{y}^2$), using the STATISTICA for Windows software [11].

3. RESULTS

Based on information provided by a timber transport company, referring to 1,387 trips made throughout the year 2020, a data compilation was made, with the results shown in Table 1.

Table 1. Compilation of wood transport data carried out by a forestry company throughout the year 2020, with an average transport distance of 110 km

	Average Volume per Trip (m ³)	Motor power (CV)	Specific fuel consumption (g/kW.h ⁻¹)	Trips	Average fuel consumption (km/l)	Average speed (km/h)
Averages ⁽¹⁾	39.03	434	319	1,387 ⁽²⁾	1.36	31.5

(1) Weighted averages by number of trips

(2) Total trips of the 16 trucks during the evaluation period

From the data in Table 1, considering each truck during the evaluation period, the necessary variables were calculated to obtain the actual energy yield, as shown in Table 2.

Table 2. Values calculated to obtain the real energetic efficiency of wood transport carried out by a forestry company throughout the year 2020

	Average consumption (l/km)	Effective consumption (l/hour)	Specific fuel consumption (g/kW.h ⁻¹)	Average Travel Time (hour)	Productivity (m ³ /hour)	Energetic Efficiency (g/kW.h/m ³)
Averages ⁽¹⁾	0.74	23.35	62.36	3.52	11.17	5.52

(1) Weighted averages by number of trips

In turn, the drying pace of the wood was estimated in periods of 10 days, in order to establish the weight x volume ratio and the technical load capacity of the trucks (in m³), respecting the Brazilian legislation on limit of weight in road transport (according to the type of vehicle composition), as well as energetic efficiency (Table 3 and Figure 2). The results presented consider a truck with a power of 440 hp, fuel consumption of 1.36 km/l and average speed of 31.5 km/h (with a total distance of 110 km, considering round trips).

Table 3. Estimation of the drying rate and energetic efficiency of wood transport

Drying days	Moisture content (%)	Volume/Weight Ratio (m ³ /ton)	Truck capacity (ton)	Truck capacity (m ³)	Energetic Efficiency (g/kW.h/m ³)
1	60.0	0.615	51	31.38	6.77
10	58.8	0.633	51	32.29	6.58
20	57.6	0.653	51	33.30	6.38
30	56.3	0.673	51	34.32	6.19
40	55.0	0.693	51	35.33	6.01
50	53.7	0.712	51	36.34	5.85
60	52.4	0.732	51	37.35	5.69

70	51.1	0.752	51	38.36	5.54
80	49.8	0.772	51	39.37	5.40
90	48.9	0.792	51	40.38	5.26
100	47.2	0.812	51	41.39	5.13
110	46.0	0.831	51	42.40	5.01
120	44.7	0.851	51	43.41	4.89
130	43.4	0.871	51	44.42	4.78
140	42.1	0.891	51	45.43	4.68
150	40.8	0.911	51	46.44	4.57
160	39.5	0.930	51	47.45	4.48

Note: wood basic density = 650 kg/m³.

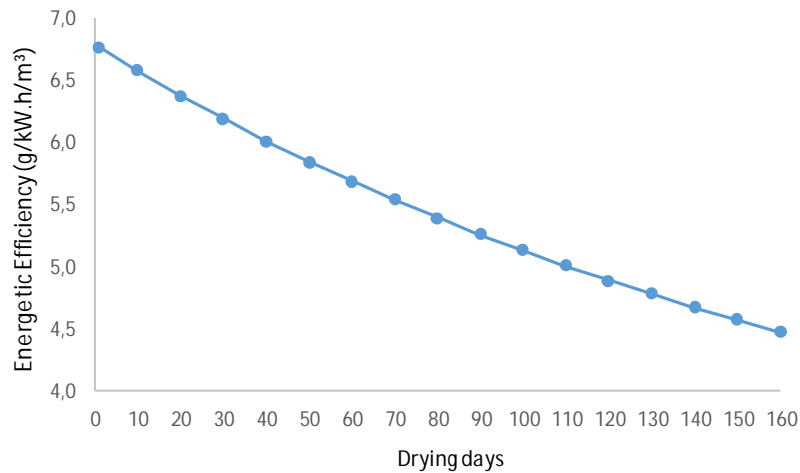


Fig. 2. Relationship between wood drying time (days) and transport energetic efficiency (g/kW.h/m³), under the study conditions

In order to verify the association between energy yield, wood drying time and the power and fuel consumption of the trucks used to transport wood, the results of the analysis of the Pearson correlation coefficient matrix (r), using the t test at 5% probability, are shown in Table 4.

Table 4. Matrix of Pearson's linear correlation coefficients between the study variables and the energy yield of wood transport

Variables	Energetic Efficiency of Wood Transport
Energetic efficiency	1
Wood weight x volume ratio	- 0,994*
Truck power	- 0,479*
Fuel consumption of trucks	- 0,635*
Transport distance	0,883*

* Significant at 5% probability, by T-test.

The results of these analyzes indicated the existence of a strong negative correlation between the evaluated variables and the energy yield of wood transport, demonstrating the importance of understanding the behavior of such variables to improve the energy yield. This strong negative correlation indicates that the drying of the wood in the field (before transport

to the consumer units), the reduction in the fuel consumption of the trucks and the increase in their power contribute, alone or jointly, to the improvement of the energetic efficiency of the wood transport.

On the other hand, the transport distance showed a strong positive correlation with the energy yield of wood transport, indicating that increases in distance contribute directly proportionally to the decrease in the energy yield of this activity.

The results of the analyzes of this study indicated that every 10 days of drying the wood in the field (starting from a humidity of 60% at the time of harvest) there is, on average, a reduction of 2.0% in the humidity of the wood and, as a consequence, an improvement of 2.8% in the energetic efficiency of wood transport, other conditions being constant.

The energetic efficiency of wood transport, for the different types of trucks evaluated, considering the moisture content of the wood, the trucks' power, fuel consumption and transport distance, was estimated by adjusted nonlinear regression equations (Table 5). The equations showed good goodness of fit, considering the estimates of the coefficients of determination (R^2), the coefficients of variation (CV%) and the correlation coefficients between the observed and estimated values squared (R_{yy}^2), presented in Table 5.

Table 5. Adjusted equations for estimating the energetic efficiency of wood transport (Y, in g/kW.h/m³), considering the moisture content of the wood (U, in %), the power of the trucks (P, in CV), fuel consumption (CC, in km/l) and transport distance (D, in km, considering round trips), for the different types of truck evaluated

Truck type	Equations	R ²	CV(%)	R _{yy} ²
Bi-train	$Y = -7.2708 - \frac{325.811}{U} + \frac{3467.12}{P} + \frac{9,3565}{CC} + 0.062 * D$	0.98	26.72	98.65
Tri-train	$Y = -5.2746 - \frac{236.426}{U} + \frac{2515.97}{P} + \frac{6.7875}{CC} + 0.045 * D$	0.98	21.43	99.22

4. DISCUSSION

Regardless of whether or not the industrial conversion process favors the moisture content of the wood as an important characteristic, all sectors of the forestry base value the moisture of logs and forest biomass as a factor of relevant importance in forestry logistics. The wetter the wood or forest biomass, the heavier it can be per unit volume, and with that, it will demand more resources and more energy to be handled, transported and stored [12]. In general, it can be stated that wood drying, among other benefits, promotes the reduction of wood mass, reducing transport and labor costs with its handling [13].

The transport of wood is, among all the activities necessary for the production of wood, the one that, individually, represents the highest consumption of fuel. In their study, considering an average distance of 100 km (round trip) and using forestry bit-train trucks, Souza et al. [14] found that wood transport was responsible for 12.7% of all fuel consumed over the 7 years of the wood production cycle. This fact denotes the importance of fuel consumption management in this activity.

It is important to emphasize that the variation in fuel consumption may be due to a series of factors such as type of vehicle and its technology, lifespan and vehicle maintenance, fuel quality, operating temperature, vehicle load capacity, weight of transported load, distance traveled, average speed of the route, quality of roads and infrastructure, conditions of displacement, flow and congestion of the system, topography of the route, weather conditions on the route, habits and behavior of the driver while driving, among other aspects [15, 16].

All these factors can, separately or jointly, be managed with a view to reducing fuel consumption and improving the energetic efficiency of wood transport. The results of this study allow us to state that a reduction of around 10% in fuel consumption is capable of providing an improvement of around 9.0% in the energy yield of the activity, keeping all other variables constant.

In another aspect, there is the power of the trucks used to transport wood as a factor to be managed when it is desired to obtain improvements in the energy yield of the activity. Campos et al. [17] state that small trucks would have high emission compared to trucks with large capacity to transport loads (in a ratio up to 4.4 times higher), maintaining a similar relationship in relation to fuel consumption.

Associated with this is the fact that trucks with greater horsepower are able to pull implements with greater load capacity and, consequently, with better energy yield per unit of transported load. In fact, the results of this study indicated that, keeping the other variables constant, each increase of 20 hp in the trucks' power represented a possible gain of up to 4.4% in the energetic efficiency of the activity of transporting wood.

For Silveira and Sierra [18] there are several models of trucks on the market and, at the time of purchase, the owner's choice is based on power, comfort, ease of operation and maintenance, in addition to price. Knowledge of the truck's energetic efficiency could be one more item to consider in your selection.

According to the International Energy Agency [19], in 2019 the transport sector was responsible for 25% of total global CO₂ emissions. The emission of greenhouse gases from transport tend to cause increasing damage to the environment, if measures are not taken to reduce the advance of these emissions. The use of trucks to transport loads can provide, in several situations, greater flexibility in operations. However, there is a conflict between these advantages and environmental interests due to the high levels of emissions caused by the fleet, as reported by Richardson [20].

Among the most varied types of logistics systems for cargo transport, the wood transport system is of great interest for several researches due to the growing world consumption of forest-based products associated with the environmental and social issues involved. From this perspective, considering the issue of the high energy expenditure that such transport represents, the search for improvement in the energy yield of the activity can represent an important tool for a management model based on the principles of sustainability: economically viable, socially fair and environmentally correct.

The use of regression equations makes it possible to simulate different scenarios involving the analysis variables for estimating the energy yield of wood transport. Since they have high coefficients of determination, that is, they fit well to the data, as long as the characteristics of the variables are respected, the presented equations will be able to estimate, with high precision, the energy yield values of wood transport under different scenarios.

5. CONCLUSION

The results of this study allowed us to conclude that:

- There is a strong negative correlation between the drying time of the wood in the field (before transport to the consumer units), the fuel consumption of the trucks and the increase in power in them, and the energetic efficiency of the wood transport.
- Every 10 days of drying the wood in the field (assuming a moisture content of 60% at the time of harvest) there is, on average, a reduction of 2.0% in the moisture content of the wood and, as a result, an improvement of 2.8% in the energetic efficiency of wood transport, other conditions being constant.
- A reduction of around 10% in fuel consumption is capable of providing an improvement of around 9.0% in the activity's energetic efficiency, keeping all other variables constant.
- An increase of 20 hp in truck power represented a possible gain of up to 4.4% in the energy yield of the wood transport activity.
- The adjusted equations make it possible to accurately and precisely estimate the energy yield of wood transport depending on the moisture content of the wood, the trucks' power, fuel consumption and transport distance, being an important auxiliary tool in decision-making when planning the evaluated variables.
- The search for improvement in the energy performance of the activity can represent an important tool for a management model based on the principles of sustainability.

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