

Article

Improving Environmental and Energy Efficiency in Wood Transportation for a Carbon-Neutral Forest Industry

Teijo Palander ^{1,*}, Hanna Haavikko ¹, Emma Kortelainen ¹, Kalle Kärhä ² and Stelian Alexandru Borz ³

- ¹ Faculty of Science and Forestry, University of Eastern Finland, P.O. Box 111, FI-80101 Joensuu, Finland; hanna.haavikko@gmail.com (H.H.); emma.kortelainen@storaenso.com (E.K.)
- ² Stora Enso, Forest Division, Wood Supply Finland, P.O. Box 309, FI-00101 Helsinki, Finland; kalle.karha@storaenso.com
- ³ Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Sirul Beethoven 1, 500123 Brasov, Romania; stelian.borz@unitbv.ro
- * Correspondence: teijo.s.palander@uef.fi; Tel.: +358-050-442-3302

Received: 8 October 2020; Accepted: 11 November 2020; Published: 12 November 2020



Abstract: Wood transportation is an important source of greenhouse gas emissions, which should be considered when the carbon neutrality of the forest industry is of concern. The EU is dedicated to improving technology for a carbon-neutral development. This study investigates carbon neutrality by improving road freight transportation fleets consisting of various vehicle size combinations. The environmental emission and energy efficiency of a transportation fleet were analyzed in selected wood procurement regions of Stora Enso corporation (Finland). Based on the enterprise resource planning (ERP) data (2018–2020), the environmental emission efficiency increased by 11% via 76 t-vehicles compared 64 t vehicles. The maximum reduction in fuel consumption was 26% for 92 t vehicles, though this was achieved when operations were fully adjusted to the maximum weight limit. The wood-based energy efficiency measure (wood energy/transport energy) was a useful development indicator. It showed that the adapted fleets of transportation companies support a positive development for a carbon-neutral forestry. In respect to the current legal fleet (64, 68 and 76 t), the use of 76 t vehicles increased energy efficiency most effectively, by 50%, compared to 64 t vehicles in the best region. Currently, transportation service providers and their clients are using ERP information to tailor their energy efficiency metric and to implement them locally in the transportation monitoring systems. A three-year sensitivity analysis demonstrates that the technological development of management tools to improve transportation efficiency is essential for larger and heavier vehicle utilization. In the future, the whole wood supply chain from forest to factory will also be optimized with respect to energy efficiency criterion to ensure a low-carbon forest industry.

Keywords: environment; energy; efficiency; CO₂; wood transportation; renewable wood; wood procurement; vehicle exhaust emissions; larger and heavier vehicles

1. Introduction

The European Commission seeks for efficient solutions to guide the EU countries in the attempt to consume less fossil energy. To reach a low-carbon economy [1], the major milestones set are to reach a 40% cut in carbon-related emissions by 2030 and a 60% cut by 2040 compared to 1990 [2]. In addition, the European Commission emphasizes that the change towards a low-carbon economy is feasible if



2 of 17

the transportation sectors will contribute to achieving these targets. Furthermore, the adaptation of the transportation sector is important because the European Commission has calculated that without regulations, the quantity of fossil fuel consumption will increase by 2030 as much as 80% above its level from 2005 [3–5]. Several researchers have reported that road freight transportation of the forest industry is a prominent carbon source [6–8]. This means that the transportation sector of the forest industry needs to implement efficiency improvements to ensure that both energy and environmental goals will be attained in the EU.

In Finland, the Ministry of Transport and Communications has published an action plan aiming to eliminate the fossil fuel consumption and greenhouse gas emissions in domestic transportation by 2045 [9]. According to this plan, the best solution for reaching the goals lies in an energy efficient transportation. In this respect, the national calculation system has been mainly used for the calculation of exhaust emissions and energy consumption in road transportation. Accordingly, the annual performance of truck traffic in 2018 was of approximately 3410 million kilometers covered, standing for ca. 7% of the total performance of road transportation traffic [10]. For the same period, the calculated annual fuel consumption of truck traffic was of 1,253,439 t of diesel, standing for about 32% of the fuel consumed in road transportation. Therefore, truck transportation causes almost one-third of the total exhaust emissions from road transportation [11–13]. Correspondingly, Table 1 shows the calculated annual vehicle emissions of road traffic by emission type [10]. This information could also be developed for the calculation of energy efficiency if truck payload data would be integrated into the system.

Emission Type	Emissions (t)	Share of Road Transport (%)
СО	2572	6.9
HC	303	8.1
NOX	11,130	36.6
PM	185	23.4
CH_4	52	14.0
N ₂ O	91	33.3
CO ₂	3,526,890	32.4
CO ₂ eq.	3,555,265	32.4

Table 1. Annual vehicle exhaust emissions of truck traffic by emission type in Finland.

From an environmental point of view, road transportation contributes, by more than 20%, to the climate impact, specific also to the Finnish forest industry [11]. On the other hand, road transportation is a necessary logistics service from forests to factories [14,15]. While the forest industry has made some progress towards a low-carbon economy through the development of carbon-neutral logistics in the 21st century [16–18], efforts are still needed to analyze and adapt the transportation fleets to meet the efficiency requirements of carbon-neutrality in the forest industry.

Stora Enso Wood Supply Finland is often used as an example of an organization that manages industrial logistics in its wood procurement regions, even though it does not hold its own wood transportation fleet. This wood procurement function was outsourced few decades ago to small- and medium-sized supply-chain companies [19–21]. Currently, about 200 trucks of more than 30 companies transport wood from forests to Stora Enso mills [22,23], while the transportation fleet is monitored by a synchronized transportation system (STS) of the supply-chain management [24]. An STS displays and informs the transportation managers about the transport situation of different trucks in operation at the same time. In addition, operative tools of the STS can be used to estimate the cost and environmental efficiency in different transportation regions. If the energy efficiency of the transportation fleet is known for different regions, it can also be used for tactical or strategic management of organizations for an efficient transition to larger and heavier vehicles (LHVs). This would be useful, since changes in legal restrictions of the maximum payload from 60 t to 76 t were regulated in 2013 in Finland.

In the European forest industry, fuel consumption of truck transportation has often been researched in relation to exhaust emissions [11,25–28]. In addition, energy efficiency has been studied by using various approaches [29–31]. For instance, Höök et al. [31] showed that there is an annual potential for 25 HCT (High Capacity Transportation) corridors throughout Sweden to use 20 to 90 t trucks to transport 2.5 Mt of roundwood, saving this way up to 5500 t of CO₂ emissions and EUR 3.1 M in fuel costs. Besides, some small-scale energy efficiency models and calculation methods have been developed in the field of industrial production and used in Scandinavia for this purpose [32,33]. More recently, different energy efficiency models of wood transportation have also been tested by using large real datasets (2016) available on different vehicle combinations (60, 64, 68 and 76 t) [34]. Following the comparisons, the best model resulted in a 20.5% increase of energy efficiency. An advantage of using real data as large datasets is that of using common mathematical analysis instead of statistical methods to generalize the results for the purpose of practice management. Compared to experiments based on small samples and statistical methods, mathematical methods can provide deterministic outcomes and more robust conclusions if the used datasets are large enough [35]. As such, mathematical analysis has already been used in operational planning and decision making for a long time in the forest industry. Particularly, cost minimization and cost efficiency of wood transportation operations have typically been the mathematical objectives of operational research as various decision-making alternatives were compared to each other [19,36–38]. In addition, energy and environmental efficiency have also been studied by the use of the same mathematical methods [39–41].

The long-term maximum CO_2 reduction after the change from 60 t to 76 t vehicles could be in the range of 27–32%, and it could be achieved when forest operations are to be fully adjusted to the maximum weight limit [11,29,42]. The fully-adjusted transportation situation assumes that 76 t vehicle combinations are 100% loaded on 100% of the distance they travel loaded. In addition, parameters such as the moisture content of timber, length of the timber, share of the empty running and logistical conditions can affect the weight of the load in road transportation specific to the wood procurement [19,43]. In this context, the combined environmental and energy efficiency analysis has only seldom been a research topic. Nevertheless, this approach is necessary because the wood transportation sector needs combined models for new transport systems to ensure effective transportation operations tailored to the variability of local conditions. Following that, efficiency metrics can be used more robustly in practice for the development for the evaluation and deployment of a wood transportation fleet that is more oriented towards carbon neutrality. The adoption of more carbon-neutral technologies is a part of the adaptation process that should be shown by the transportation fleet in response to the EU regulations [1-4,44]. In essence, this process is achieved by a better environmental efficiency which characterizes larger and heavier vehicles [11,28]. Recent studies have shown that the increase in energy efficiency of transportation fleets depends also on the road transportation infrastructure and on the type of fleet management [17,23,31,34]. However, such studies have analyzed and considered the efficiency in the early phase of the adaptation process (before 2016), and they characterized only the potential impacts on the environmental benefits.

After a six-year adaptation process this study investigates both the environmental and energy efficiency of transportation fleets in the current, more mature transport situation (2020) of Finland. The rationale of the study is framed around a more profound understanding of the combined efficiency measurement models as a prerequisite for engaging in a deeper mathematical planning of the transportation sector. It was hypothesized that the transportation development situation of different wood procurement regions might have an impact on the usefulness of both efficiency metrics. In addition to different development situations, effects of characteristics of the vehicle loads are different since the wood (load assortments) may be loaded from various and several roadside inventories. Besides the tests done on the selected mathematical energy-efficiency model [34], this study introduces a novel calculation method that aimed to enable the comparison of environmental efficiency of the wood transportation operational alternatives. As such, the objectives set for this study were the following: (i) to calculate the environmental and energy efficiency of the wood transportation fleet for

the timeframe of 2018 to 2020 and (ii) to evaluate the usefulness of the efficiency metrics in the current mature development situation to achieve the maximum efficiency state of transportation fleets.

2. Materials and Methods

2.1. Wood Transportation Data

Wood transportation data were collected from the enterprise resource planning (ERP) system between 6 July 2018 and 19 August 2020. The system was used to automatically collect digital data from 210 vehicles (Table 2), which included all the deliveries to the corporation i.e., the research observations. In addition to data ranges, standard deviations were calculated to illustrate the variation of data, although no statistical sampling methods were required or used for data collection.

Devenestor	Measurement		Vehicle Combination					
rarameter	Unit	64 t	68 t	76 t	92 t			
Share of measured loads	%	1	14	84	1			
Transportation distance—average	km	83	72	76	165			
Transportation distance—range	km	1–294	1-439	1-626	14-303			
Transportation distance—standard deviation	km	59	53	52	61			
Transportation distance—median	km	75	60	65	146			
Load size—average	t	42	43	50	65			
Load size—range	t	1–71 ¹	1–98 ¹	1–113 ¹	48–69 ¹			
Load size-standard deviation	t	8	14	8	3			
Load size—median	t	43	47	52	65			
Fuel consumption—average	$L \times 100 \text{ km}^{-1}$	58	59	62	73			
Fuel consumption—range	$L \times 100 \text{ km}^{-1}$	35–66	37–73	39–76	42–91			

Table 2. Description of the main wood transportation parameters for the 2018–2020 interval.

¹ Load sizes larger than the typical capacity are the effect of some minor ERP technical mistakes that were kept into analysis since their effect on the results was insignificant.

2.2. Wood Transportation Conditions

The data pool used in analysis included information from 442,269 wood deliveries from forests to factories. The range of the load size of the vehicles was very large, because the ERP dataset included some technical errors that were also kept in the analysis. However, their effects on the results were insignificant. Data accounting for 15% of the delivered wood characterized transports done by 64 and 68 t vehicle combinations, whereas 76 t combinations accounted for 84% of the data. Load share of the 92 t vehicle combinations (HCT, i.e., high capacity transportation) was about 1%. As shown in Figure 1, the total quantity transported by various vehicle combinations was of about 538 million kilometric tons (tkm). In reality, the ERP material consists of the average values regarding the wood assortments that are loaded into the vehicles based on harvesting data available for each stand, which is generated/measured by the harvesting machines. In addition, the ERP contains data characteristic to different regions, which is useful when reporting results for selected regions of wood procurement. In this study, the usefulness of the energy efficiency metric was evaluated by using these characteristics after a six-year adaptation process. The transportation development situations of different wood procurement regions are described by the data collected from three selected regions (Table 3) [34]. The same data characteristics were collected and analyzed after the former period (2014–2016). Discussion and conclusions of this study are based on the comparison with the research from this latter period.



Figure 1. Transportation quantity (tkm) of vehicle combinations. Legend: F—forest roads and roads with speed limit <60 km × h⁻¹, H—highways and other roads with speed limit \ge 60 km × h⁻¹.

	Measurement		Region A			Region B				Region C			
rarameter	Unit	64 t	68 t	76 t	92 t	64 t	68 t	76 t	92 t	64 t	68 t	76 t	92 t
Number of loads	-	625	7550	72,159	158	392	4763	46,890	196	13	2036	48,264	259
Average load size	t	46	46	50	66	40	46	50	64	52	48	49	65
Fuel consumption as loaded	$L \times 100 \text{ km}^{-1}$	59	60	61	73	58	60	61	72	62	61	61	73
Fuel consumption of loaded trip	kWh	768	545	568	1099	811	559	568	1574	437	444	561	1142
Fuel consumption of empty trip	kWh	709	503	525	1014	748	516	525	1453	403	410	518	1054
Energy content of the loads	kWh	41,634	44,084	45,255	73,793	29,815	34,288	39,931	61,334	55,371	51,112	49,568	76,136
Empty driving distance	km	101	70	72	116	108	72	72	169	54	56	71	121
Loaded driving distance	km	109	76	78	126	117	78	78	183	59	61	77	131
Number of plants	-	11	11	11	11	6	6	6	6	4	4	4	4
Highways with speed >60 km \times h ⁻¹	km	1468	1468	1468	1468	737	737	737	737	501	501	501	501
Local roads with speed $\leq 60 \text{ km} \times \text{h}^{-1}$	km	1407	1407	1407	1407	784	784	784	784	1051	1051	1051	1051

Table 3. Wood transportation conditions for vehicle combinations of 64, 68, 76 and 92 t in the procurement regions A, B and C (2018–2020).

To enable data comparison between this study to that from previous studies, fuel consumption of the vehicle combinations was calculated by the same method [11,34]. In the dataset, the fuel consumption was determined for the 64 and 76 t vehicle combinations by considering different sizes of the payloads. The fuel consumptions of 68 and 92 t combinations were obtained by calculating the linear fuel consumption increment over the range of consumption values from 60 to 76 t vehicle combinations. As an example, for a 37 t payload, the average fuel consumption of a 64 t vehicle is 0.5 L per 100 km higher than the consumption of the 60 t combination. Correspondingly, the average fuel consumption of the 68 t combination is one liter per 100 km higher than the consumption of a 60 t vehicle combination. Furthermore, the difference between the fuel consumption of the 76 and 60 t combinations is two liters per 100 km. Empty 60, 64, 68 and 76 t vehicle combinations consume 34, 35, 36 and 38 L per 100 km, respectively. It was mentioned above that fuel consumption varies depending on the payload size and, as a fact, fuel consumption was determined by using the theoretical gradual increment of the load size. For example, when the payload size was in the range of 37–40 t, the average consumption of 60 t vehicle stayed at about 58 L per 100 km and it increased at 58.7 L when the load size was in the range of 41–44 t. When the load size exceeded 50 t, fuel consumption increased following a linear rate of 0.7 L per 100 km for each ton in addition.

2.4. Environmental Efficiency

The load emission data from VTT's Lipasto database [10] was combined with the wood transportation data following the exhaust emission procedure outlined by McKinnon [12]. This method was developed further in this study to support the calculation of the parameters characterizing the environmental efficiency. To support the exhaust emission calculation method, information on the impact of load constraints was collected in accordance with the statistical directive published by the EU [45]. It was assumed that only vehicles meeting the Euro VI emission standard or above would be allowed to operate as larger and heavier vehicles (LHV), as shown in Table 4. This standard was introduced in 2013 by the European Commission for new, heavy-duty, diesel engines of trucks, and it regulates the maximum level of emissions for CO, HC, NOx and PM [46].

Table 4. Standards of vehicle exhaust emission for new, heavy-duty, diesel engines, in g kWh⁻¹ [45]. CO—carbon monoxide, HC—hydrocarbons, NOx—nitrogen oxides and PM—particulates.

Stage	Year	СО	HC	NOx	PM
EURO IV	2005	1.5	0.46	3.5	0.02
EURO V	2008	1.5	0.46	2.0	0.02
EURO VI	2013	1.5	0.13	0.4	0.01

In this paper, the environmental efficiency of each transportation unit was estimated based on the methods proposed by Hu and Wang and Chang et al., respectively, [39,40] where the index of total efficiency was introduced by using the optimal energy input level, and on the applications of Zhou and Ang and Park, respectively, [41,47] of evaluating efficiency with undesirable output. In respect to the CO₂ emissions, the environmental efficiency (CEE) can be calculated as follows (Equation (1)):

$$CEE = Target CO_2 \ emission/Real \ CO_2 \ emission = (C_o - C_s)/C_o, \tag{1}$$

where C_o is the observed CO₂ emission, and C_s is the slack/reference/base value of CO₂ emission. Therefore, the value of $C_o - C_s$ is the target CO₂ emission level that could be e.g., set or optimized at the minimum level. In this study, the target level of CO₂ emission was set for the 76 t vehicle combination, because this vehicle combination was targeted as the legal maximum vehicle size of the transportation fleet. Often, the performance improvement of each input and output indicator is evaluated in terms of percentage. Here, percentages of this measurement unit were only used in the text to support the discussion of the main results.

The environmental efficiency of each transportation vehicle was determined by calculating vehicles' CO_2 emissions per tonne-kilometre and by comparing the emission values to the emission of the 76 t vehicle. To this end, Equation (1) was used to produce the results at this level. The analysis was done to account for the variation in wood deliveries which was described by the standard deviation of the load size.

2.5. Energy Conversion

Diesel fuel belongs to the category of light fuel oils, the density of which, according to season (winter/summer), varies between 800 and 850 kg m⁻³ [48–52]. A diesel density of 840 kg m⁻³ was used in the calculations of this study. Fuel consumption of wood transportation is often expressed in liters per 100 km (L \times 100 km⁻¹); however, the quantity of diesel consumed in wood transportation was calculated in kilograms. Conversion into energy was done using the net calorific value conversion factor, which is $43 \text{ MJ} \times \text{kg}^{-1}$ for light fuel oils [53]. The amount of consumed energy, expressed in kWh, was calculated using the regular factor of 3.6 MJ per kWh. The energy contained in the transported wood was calculated by using the net calorific value of the wood. The calculation has used the net calorific value of the dry wood, set at 19.167 MJ \times kg⁻¹. This figure stands for the mean value of birch, pine and spruce species [54]. In addition, the energy content was accounted by using two different percentages of the wood moisture content, namely 35 and 55%. The moisture content of industrial wood is about 55%. For the energy generation the moisture content is targeted to decrease before burning to the 35%. Payload of a vehicle combination was multiplied by the net calorific value and the results of energy content were reported in kWh per ton (Equation (2)). If the wood is burned (e.g., in heating plants), then the net calorific value in the arrival mode decreases when the moisture content percentage increases because the evaporation of water uses energy, a fact that was taken into account in the calculation of the energy generation. When the wood is used for energy generation e.g., in combined heat and power (CHP) plants the net calorific value of the fuel in the arrival mode is obtained using the Equation (2).

$$Q_{net,ar} = ((Q_{net,d} \cdot (100 - M_{ar})/100 \cdot 1000) - (c \cdot M_{ar} \cdot 1000))/3.6,$$
(2)

where $Q_{net,ar}$ is the net calorific value of the transported wood, in kWh × t⁻¹; $Q_{net,d}$ —net (lower) calorific value of the dry wood, in MJ × kg⁻¹; M_{ar} —moisture content of the wood at the time of arrival, in %; c—a constant of 0.02 MJ × kg⁻¹ which equivalates water evaporation rate at a temperature of 25 °C. The situation is different in the industrial use: e.g., the pulp sector uses feedstock, wood, which can likewise be used as an energy source. The dual character of the feedstock puts an extra burden on the data and calculation. How energy is calculated and allocated depends a lot on the intended use of the wood. In this study, the effect of evaporation of water was omitted from the net calorific value in the arrival mode in the industrial use. This calculation represents a theoretical potential of wood energy content in the industrial integration.

2.6. Energy Efficiency

The energy efficiency of the STS was analyzed using the physics formula. The energy efficiency (i.e., the efficiency ratio of the energy transported and consumed) is calculated using Equation (3) which was developed and tested by Palander et al. [34].

$$E_{eff} = E_{tran}/E_{con},\tag{3}$$

where E_{eff} is the energy efficiency; E_{tran} is the amount of energy transported, in kWh; E_{con} is the amount of energy consumed, in kWh.

Equation (3) defines an energy efficiency metric that takes into account the ratio of efficiency characterizing the payload of wood energy to that of the fuel consumption for a vehicle combination. By considering this metric, the most energy-efficient combination is that which gets the highest value [53]. Furthermore, the equation accounts for the moisture content of the wood which directly influences the net calorific value in the arrival mode to a destination and, by doing so, it also influences the amount of energy contained in a vehicle combination. In addition to the physics formula, this Equation (3) is, in theory, a natural wood resource-based energy efficiency measure. Based on the comparison of the STS energy efficiencies, the metric enables the development of an effective transportation fleet (vehicle combinations) for given wood procurement regions.

3. Results

The environmental emission efficiency of wood transportation was analyzed by assuming the average conditions of distance, weight and efforts in terms of mass moved over the distance (tkm). The results characterizing the selected wood deliveries are shown in Figure 2 for two categories of roads: forest roads and highways. As shown, the CO_2 emissions retained almost the same level, although larger and heavier vehicles were used in transportation. Compared to regular vehicle combinations (64 t) the results showed that the average CO_2 emissions of 76 t vehicles used for a two-way transport per 300 km were 5% higher for the average loads.



Figure 2. CO₂ emissions of wood transportation accounting for the transportation distance and vehicle weight.

Correspondingly, when the loads were delivered to their destinations, the 64 t vehicle combination consumed 4.9% less energy per kilometer than the 76 t vehicle combination. However, the overall emissions actually decreased if the results are considered in tonne-kilometers (tkm) because of reduced fuel consumption per transported unit. A more detailed exhaust emission analysis of the transportation fleet is given in Table 5. It shows how the reduction in fuel consumption and the corresponding emissions of environmental contaminants decreased as the road transportation sector was developed to the 92 t weight limit. For example, emissions of CO_2 were reduced by 22.7% to a figure of 27.1 g × tkm⁻¹ during this adaptation process of the transportation system from 2018 to 2020. The reduction in fuel consumption between 76 and 64 t vehicles was 10.7%.

Emissions (g \times tkm ⁻¹)		64 t ¹			76 t ¹		92 t ¹		
	F ²	H ²	AR ²	F ²	H ²	AR ²	F ²	H ²	AR ²
CO ₂	38.251	34.965	35.1293	34.092	31.233	31.376	28.329	27.080	27.143
SO_2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
NOx	0.0099	0.0082	0.0083	0.0080	0.0063	0.0064	0.0067	0.0055	0.0055
СО	0.0052	0.0038	0.0039	0.0042	0.0030	0.0031	0.0035	0.0026	0.0027
PM	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
HC	0.0008	0.0006	0.0006	0.0007	0.0005	0.0005	0.0006	0.0004	0.0004
N ₂ O	0.0009	0.0014	0.0014	0.0007	0.0011	0.0011	0.0006	0.0010	0.0010
CH_4	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Fuel $(L \times tkm^{-1})$	0.016	0.014	0.015	0.014	0.013	0.013	0.012	0.011	0.011

Table 5. Exhaust emissions and fuel consumption of wood transportation.

¹ Maximum weights of loaded vehicles are of 64, 76 and 92 t, respectively; ² F—forest roads, H—highways and AR—all roads.

Table 6 shows the environmental efficiencies of the vehicle combinations in respect to the average loaded 76 t vehicle combination. Table reveals that 64 and 68 t vehicle combinations were more efficient than 76 t vehicles when 42 t loads were delivered to plants. This calculation method accounts also for load variation that may produce heavier vehicle weights (illegal loads), which sometimes may happen in practice. For example, a 68 t vehicle would be the most efficient vehicle combination for delivering 50 t loads, if this approach would be legal. This metric can used to comparing transport operations, i.e., wood deliveries of the vehicle combinations.

Table 6. The environmental efficiency (EE) of vehicle combinations of wood transportation accounting for the load size (L) and vehicle weight.

64 t ¹		68	5 t ¹	76	5t ¹	92 t ¹		
L	EE ²	L	EE ²	L	EE ²	L	EE ²	
34	0.72	29	0.60	42	0.83	62	1.05	
38	0.80	36	0.74	46	0.91	64	1.08	
42	0.88	43	0.89	50	1.00	65	1.10	
46	0.96	50	1.04	54	1.08	66	1.13	
50	1.04	57	1.18	58	1.16	68	1.16	

 1 Maximum weights of loaded vehicles are of 64, 68, 76 and 92 t respectively. 2 Environmental efficiency based on CO₂ emissions.

The average energy content of the transported wood was calculated for both moisture contents by using Equation (2). Results from the energy conversions are presented to illustrate the effect of moisture evaporation in wood transportation situations for the period of 2018–2020. Table 7 shows the average energy content of fuel consumption and the amount of energy transported as wood by loads of the vehicle combinations with various wood moisture percentages. The amount of energy transported as wood correlates negatively with the wood moisture content (%). For example, the energy content of the average wood load (50 t, 76 km) of the 76 t vehicle combination was 1.6 times higher when the percentage of moisture content changed from 55 to 35% for energy generation of a CHP plant of the corporation.

The energy efficiency of the vehicle combinations was analyzed by using Equation (3). The energy efficiency metric characterizes an energy relation of the transportation, i.e., the ratio of payload's wood energy to vehicle's fuel consumption (kWh kWh⁻¹). The energy efficiency was different for each combination. A simple example which characterizes the situation 2020, is presented in Figure 3 that indicating the 92 t vehicle combination as the most efficient one in the entire wood-procurement region, while the 76 t vehicle combination was the second in this kind of ranking. It performed 19% better in terms of energy efficiency compared to the 64 t combination, as shown in Figure 3. Due to the higher

capacity of LHVs (68, 76 and 92 t) the energy efficiency of wood transportation increased by 25% for the measured loads.

Energy Type	Moisture	Energy Content ¹ (kWh × tkm ⁻¹)							
	Content (%)	6 4	64 t		3 t	76	5 t	92	2 t
		I ²	E ²	I ²	E ²	I ²	E ²	I ²	E ²
FC	-	139	139	138	138	123	123	111	111
WE	55	1304	88	1335	90	1553	105	2018	136
WE	35	1884	137	1929	140	2243	163	2915	212

Table 7. Average fuel consumption (FC) and the amount of energy contained in the wood (*WE*) for loaded vehicle combinations of 64, 68, 76 and 92 t.

¹ Figures are based on average payloads of 42, 43, 50 and 65 t and transport distances of 83, 72, 76 and 165 km, respectively; ² I—wood for industry, E—wood for energy generation.



Figure 3. A comparison of energy efficiency based on vehicle combinations and two moisture contents (35 and 55%). Legend: I—wood for industry; E—wood for energy generation.

In addition, to indicate the most energy-efficient vehicle combination, this metric can be used to compare different transportation fleets operating in different transportation development situations. The usefulness of energy efficiency metric was analyzed firstly by using the data of this study and, secondly, in comparison to the results provided by previous studies to see if the energy efficiency achieved the theoretical maximum. Both approaches showed the usefulness of the metric used in comparing the development of transportation fleets at the local scale.

The ranking of vehicle combinations in relation to their energy efficiency varied in relation to the region of procurement (Figure 4). For example, the 76 t vehicle combination was found to be the best option in the regions A and B, while the 64 t combination was the best option in the region C. In the regions A and B, the 76 t vehicle combination performed, on average, 117% better than the 64 t combination in terms of energy efficiency. However, in region, C the 64 t vehicle combination performed 7% better in terms of energy efficiency compared to the 76 t vehicle combination. It is also

worth noticing that the transportation fleet of region C was the most evenly distributed in what regards the energy efficiency of all vehicle combinations. As such, in this transportation fleet, the energy efficiency can be increased quite evenly by the use of these vehicles. In the other regions (A and B), the situation was different. For example, in the transportation fleet of the region B, energy efficiency can be increased effectively if the fleet is adapted first, or most often, to use the 68 and 76 t vehicle combinations instead of the 64 and 92 t vehicle combinations. If the energy efficiency is used as the indicator in this comparison, the STS of region C performed 50% better compared to the STS of region B.



Figure 4. A comparison of energy efficiency based on the vehicle combinations of wood-transportation fleets in the selected wood-procurement regions (A, B and C).

4. Discussion

In this study, the environmental emission efficiency and energy efficiency of the transportation fleet were calculated for the reference year of 2020, accounting for an increment in the use of larger and heavier vehicles. In addition to the former method used for the calculation of environmental emissions [11], the novel mathematical method and model (Equation (1)) was developed and tested for the calculation of environmental efficiency, which was used as the environmental efficiency metric of CO₂ emissions. Then, the usefulness of both metrics was evaluated in the process of development progress characterizing the wood transportation fleet, which included 64, 68, 76 and 92 t vehicle combinations. The results describe a mature situation of the development process towards the maximum efficiency of partial fleets. These results are then compared with the results of the previous studies [11,34] which describe the development state of the transportation fleet of the same forest industry corporation at an earlier phase, as before the end of 2016. It was expected that both the efficiency measurement methods would have been able to reveal minor changes between the phases, which could be used in this mature stage of the development process towards a maximum efficiency. The energy efficiency model (Equation (3)) was used as the energy efficiency metric that characterizes the relationships between the energy of a payload and the fuel consumption of a vehicle. The described approach was selected and used as it was proved to yield accurate results by a recent study [32].

Vehicle combinations of 64, 68, 76 and 92 t were used in the fleets from 2018 to 2020, since the six-year adaptation process from 2014 to 2020 shifted the fleet towards the use of larger and heavier vehicles—also called a high capacity transportation. There has also been a change from 60 to 64 t vehicle combinations during the study period of 2014–2016. The main change that occurred in the fleet during the period 2017–2020 was that the 60 t vehicle combinations (5%...1%) were replaced by the 76 t combination (67%...85%) (Table 2). It is also worth noticing that share of 76 t vehicles was null in

2013. During both of the study periods, the changes that occurred in the fleet contributed by an increment of environmental benefits, because the exhaust emissions decreased by 9.2% and 10.7%, respectively, based on the results calculated per tkm. As such, the changes from the latter period increased the average environmental emission efficiency by 1.5%. It is clear, however, that all of expected environmental benefits will not be reached in the STS, because smaller loads can be delivered more efficiencly (6%) by using 64 and 68 t vehicle combinations; this was proven by the environmental efficiency metric. Finnish studies have reported that if the 60 t vehicle combinations are to be replaced by 76 t combinations, the 76 t option could reduce CO_2 emissions even by 32% [30]. Although these very optimistic environmental goals cannot be reached, the wood-based energy efficiency metric revealed that wood transportation was already carbon neutral in 2020. The results are consistent with those of previous studies [24,34]. On the other hand, it is worth noticing that the larger and heavier vehicles require wider and more robust paving systems of the forest roads and they could be a problem for public roads too, because of their negative environmental implications if the share of the HCT is to be increased compared to its current level. To this end, and besides the transport systems and corridors [5,31], European road transport infrastructure should be investigated thoroughly.

According to a former study [34] referring to the 2014–2016 period, the use of 68 t vehicles was found to increase the energy efficiency most effectively, while this study pointed out that the use of 76 t vehicles was the most successful option. This change can be justified because the transportation fleet of 2016 was not in its current, mature state. In the current phase of the adaptation process, the most efficient 76 t vehicles operated in the wood-procurement regions A and C; this meant an energy efficiency increment of 117.0% compared to the use of 64 t vehicles. In the previous studies [24,34], the region C was the most problematic in what regards the structure of the fleet, which was adapted prior the period of this study. Nowadays, the region *C* is the most balanced one in relation to the vehicle mix. It was also the most energy-efficient region, according to this study. Therefore, the tested development indicator is a useful tool for tactical and strategic transportation planning. The result confirmed that the energy efficiency of the STS is dependent on the local transportation conditions. Together, these conditions affect vehicle routing, optimization and scheduling alternatives of transportation fleets in large forest industry corporations [24,31,34]. The studied transportation organizations deliver wood to a large forest industry company in Finland and the transported volume, used as a reference for this study, stands for about one-third of the wood delivered at the Finnish mills, which is 23 million m³ per year [22,23]. Therefore, the results of this study stand for a good representation of the current wood transportation development situation in Finland. Furthermore, the large dataset collected in real time and used in this study justifies very well the use of mathematical calculation methods instead of statistical approaches.

The results of this study suggest that the environmental efficiency metric can be used as an operative state indicator in the development process if the exhaust emissions are to be calculated per tonne-kilometre, accounting this way for the relative fuel consumption. As such, it is a particularly useful tool for monitoring operations in practice. This suggestion was generalized from the results. On the other hand, the wood-based energy efficiency metric is recommended as a useful indicator to estimate the level of energy efficiency reached by transportation fleets. Furthermore, the indicator stands for a useful tool for tactical and strategic planning in the adaptation process of the transportation fleet towards maximum benefits, a process which, as shown by this study, is almost completed in Finland. Several studies have recommended environmental efficiency metrics for this kind of analyses [46]. However, based on the results of this study, they are mainly useful for operational management practices. Therefore, the results of this study suggest that instead of the environmental efficiency metric the energy efficiency metric are needed to spatial scenario analysis of transportation fleets to achieve all of possible benefits under impacts of local wood transportation conditions. Last but not least, this study provides updated information in relation to the transportation fleets in the mature wood transportation development situation, which is novel knowledge compared to previous studies in the EU.

5. Conclusions

Forest companies can address their environmental and energy efficiency responsibilities by developing a carbon-neutral wood transportation. In this study, a minor positive development was found at the end of the adaptation process. The results of the environmental efficiency metric show that larger and heavier transportation vehicles have reduced the exhaust emissions specific to single trucks and 76 t vehicles should be used fully loaded. In reality, the wood-based energy efficiency metric (payload's wood energy/transport energy) shows that the adaptation process of the transportation fleet towards 76 t vehicles is almost completed. The metric revealed that the changes of transportation efficiency were positive towards the maximum efficiency between the beginning of period 2014–2016 and the end of period 2017–2020, i.e., the vehicles transported more energy embodied in the wood for production than they consumed fossil energy. In respect to the discussion related to the carbon balance, wood transportation would support the positive regional development of forest carbon sinks. Therefore, the efficiency metrics should be implemented in the transportation planning and monitoring systems and applications. Similarly, other forest-industry companies can apply the environmental and energy efficiency indicators in their transportation conditions and development situations. In addition to transportation, however, the entire wood-procurement logistics, from forest to production facilities, should be analyzed and optimized by the use of multiple criteria including cost minimization and maximization of energy and environmental emission efficiency, which would ensure profitable and low-carbon production processes.

Author Contributions: Conceptualization, T.P. and K.K.; methodology, T.P. and E.K.; software, T.P. and E.K.; formal analysis, T.P and H.H.; data curation, K.K. and H.H.; writing—original draft preparation, T.P.; writing—review and editing, T.P., H.H., E.K., S.A.B. and K.K.; visualization, T.P. and S.A.B; supervision, T.P.; funding acquisition, S.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to the University of Eastern Finland and to the Transilvania University of Brasov for financial and technical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

- EUR-Lex. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52011AE1389 (accessed on 2 March 2020).
- EUR-Lex. A Policy Framework for Climate and Energy in the Period from 2020 to 2030. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0015&from=EN (accessed on 2 March 2020).
- 3. Korzhenevych, A.; Dehnen, N.; Bröcker, J.; Holtkamp, M.; Meier, H.; Gibson, G.; Varma, A.; Cox, V. *Update of the Handbook on External Costs of Transport*; European Commission, DG Mobility and Transport: Ispra, Italy, 2014.
- 4. OECD. Moving Freight with Better Trucks: Improving Safety, Productivity and Sustainability. 2011. Available online: http://www.oecd-ilibrary.org/transport/ (accessed on 2 March 2013).
- García-Olivares, A.; Solé, J.; Samsó, R.; Ballabrera-Poy, J. Sustainable European Transport System in a 100% Renewable Economy. *Sustainability* 2020, *12*, 5091. [CrossRef]
- Handler, R.M.; Shonnard, D.R.; Lautala, P.; Abbas, D.; Strivastava, A. Environmental impacts of roundwood supply chain options in Michigan: Life-cycle assessment of harvest and transport stages. *J. Clean. Prod.* 2014, 76, 64–73. [CrossRef]
- Sonne, E. Greenhouse gas emissions from forestry operations: A lifecycle assessment. J. Environ. Qual. 2006, 35, 1439–1450. [CrossRef]
- 8. Ghose, A.; Chinga-Carrasco, G. Environmental aspects of Norwegian production of pulp fibers and printing paper. *J. Clean. Prod.* **2013**, *57*, 293–301. [CrossRef]

- 9. Ministry of Transport and Communications, Transport Emissions to Zero by 2045. Available online: https://valtioneuvosto.fi/en/article/-/asset_publisher/liikenteen-paastot-nollaan-vuoteen-2045-mennessa (accessed on 2 March 2020).
- 10. Lipasto, Road Traffic Emissions and Energy Consumption in Finland, 2012. Available online: http://lipasto.vtt.fi/liisae/emissiondata.htm (accessed on 2 March 2020).
- 11. Palander, T. The environmental emission efficiency of larger and heavier vehicles—A case study of road transportation in Finnish forest industry. *J. Clean. Prod.* **2017**, *155*, 57–62. [CrossRef]
- 12. McKinnon, A. The economic and environmental benefits of increasing maximum truck weight: The British experience. *Transp. Res. Part D Transp. Environ.* **2005**, *10*, 77–95. [CrossRef]
- McKinnon, A.C.; Piecyk, M. Measurement of CO₂ emissions from road freight transport: A Review of UK Experience. *Energy Policy* 2009, *37*, 3733–3742. [CrossRef]
- 14. Korhonen, J. Four ecosystem principles for an industrial ecosystem. J. Clean. Prod. 2001, 9, 253–259. [CrossRef]
- 15. Korhonen, J. A material and energy flow model for co-production of heat and power. *J. Clean. Prod.* **2002**, *10*, 537–544. [CrossRef]
- Palander, T.; Kärhä, K. Characteristics of energy performance measures for 100% carbon-neutral wood procurement of forest industry. In *New Trends in Nanotechnology, Material and Environmental Sciences*; Zhu, J., Jin, A., Zhu, D., Eds.; AV AkademikerVerlag: Berlin, Germany, 2018; pp. 304–332.
- 17. Palander, T.; Haavikko, H.; Kärhä, K. Towards sustainable wood procurement in forest industry—The energy efficiency of larger and heavier vehicles in Finland. *Renew. Sustain. Energy Rev.* **2018**, *96*, 100–118. [CrossRef]
- 18. Green and Vibrant Economy—The Climate Roadmap for the Forest Industry. Available online: https://www.metsateollisuus.fi/ilmastotiekartta/ (accessed on 2 March 2020).
- 19. Palander, T.; Väätäinen, J. Impacts of inter-enterprise collaboration and backhauling on wood procurement in Finland. *Scand. J. For. Res.* 2005, 20, 177–183. [CrossRef]
- 20. Palander, T.; Säynäjärvi, T.; Högnäs, T. New organizing models of timber truck transportation. *Metsätieteen Aikakauskirja* **2006**, *1*, 5–22. (In Finnish)
- 21. Palander, T.; Vainikka, M.; Yletyinen, A. Potential mechanisms for co-operation between transportation entrepreneurs and customers: A case study of regional entrepreneurship in Finland. *Croat. J. For. Eng.* **2012**, *33*, 89–103.
- 22. Stora Enso, Progress Book, Part of Stora Enso's Annual Report 2017, 2018. Available online: https://www.storaenso.com/download-centre/ (accessed on 2 March 2020).
- 23. Haavikko, H.; Kärhä, K.; Hourula, M.; Palander, T. Attitudes of small and medium-sized enterprises towards energy efficiency in wood procurement: A case study of Stora Enso in Finland. *Croat. J. For. Eng.* **2019**, *40*, 107–123.
- 24. Palander, T.; Kärhä, K. Improving energy efficiency in a synchronized road-transportation system by using a TFMC (Transportation Fleet-Management Control) in Finland. *Energies* **2019**, *12*, 670. [CrossRef]
- 25. Holzleitner, F.; Kanzian, C.; Stampfer, K. Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. *Eur. J. For. Res.* **2011**, *130*, 293–301. [CrossRef]
- 26. Svenson, G.; Fjeld, D. The impact of road geometry, surface roughness and truck weight on operating speed of logging trucks. *Scand. J. For. Res.* **2017**, *32*, 515–527. [CrossRef]
- Lijewski, P.; Merkisz, J.; Fuć, P.; Ziółkowski, A.; Rymaniak, L.; Kusiak, W. Fuel consumption and exhaust emissions in the process of mechanized wood extraction and transport. *Eur. J. For. Res.* 2017, 136, 153–160. [CrossRef]
- 28. Palander, T. Environmental benefits from improving transportation efficiency in wood procurement systems. *Transp. Res. Part D Transp. Environ.* **2016**, *44*, 211–218. [CrossRef]
- 29. Liimatainen, H.; Pöllänen, M. Trends of energy efficiency in Finnish road freight transport 1995–2009 and forecast to 2016. *Energy Policy* **2010**, *38*, 7676–7686. [CrossRef]
- Hämäläinen, E.; Hilmola, O.P. Energy efficiency at the paper mill—Dilemma of improvement. *Energy Effic.* 2017, 10, 809–821. [CrossRef]
- 31. Höök, C.; Asmoarp, V.; Edlund, B.; Bergström, D. A Method of Finding HCT Roundwood Corridors for Reduction of GHG Emissions and Fuel Costs in Sweden. *Forest* **2020**, *11*, 220. [CrossRef]
- 32. Joelsson, J.M.; Gustavsson, L. CO₂ emission and oil use reduction through black liquor gasification and energy efficiency in pulp and paper industry. *Resour. Conserv. Recycl.* **2008**, *52*, 747–763. [CrossRef]

- 33. Kilponen, L.; Ahtila, P.; Parpala, J.; Pihko, M. Improvement of pulp mill energy efficiency in an integrated pulp and paper mill. In Proceedings of the 2001 ACEEE Summer Study on Energy Efficiency in Industry, Tarrytown, NY, USA, 24–27 July 2001; pp. 363–374.
- Palander, T.; Haavikko, H.; Kortelainen, E.; Kärhä, K. Comparison of energy efficiency indicators of road transportation for modeling environmental sustainability in "Green" Circular Industry. *Sustainability* 2020, 12, 2740. [CrossRef]
- 35. Taha, H.A. Operations Research: An Introduction, 10th ed.; Pearson: London, UK, 2017.
- 36. Palander, T. Local factors and time-variable parameters in tactical planning models: A tool for adaptive timber procurement planning. *Scand. J. For. Res.* **1995**, *10*, 370–382. [CrossRef]
- Palander, T. Tactical Models of Wood-Procurement Teams for Geographically Decentralized Group Decision-Making. Ph.D. Thesis, University of Eastern Finland, Joensuu, Finland, 1998. Available online: https://www.researchgate.net/publication/44364975_Tactical_models_of_wood-procurement_teams_ for_geographically_decentralized_group_decision-making_Teijo_Palander (accessed on 22 October 2020).
- 38. Carlsson, D.; Rönngvist, M. Backhauling in Forest Transportation—Models, Methods and Practical Usage. *Can. J. For. Res.* **2007**, *37*, 2612–2623. [CrossRef]
- Hu, J.; Wang, S. Total-factor energy efficiency of regions in China. *Energy Policy* 2006, 34, 3206–3217. [CrossRef]
- 40. Chang, Y.-T. Environmental efficiency of ports: A data envelopment analysis approach. *Marit. Policy Manag.* **2013**, *40*, 467–478. [CrossRef]
- 41. Chang, Y.-T.; Zhang, N.; Danao, D.; Zhang, N. Environmental efficiency analysis of transportation system in China: A non-radial DEA approach. *Energy Policy* **2013**, *58*, 277–283. [CrossRef]
- 42. Ministry of Transport and Communications. Better Competitiveness through New Masses and Dimensions for Heavy Goods Vehicles. 2013. Available online: http://www.lvm.fi/tiedote/4150413/better-competitiveness-through-new-masses-and-dimensions-for-heavy-goods-vehicles (accessed on 2 March 2020).
- 43. Palander, T.S. A model to estimate benefits from log drying for supply chains in wood procurement. In Proceedings of the 2nd World Symposium on Logistics in Forest Sector, IUFRO and Wood Logistics Network, Växjö, Sweden, 12–15 August 2001; Available online: https://www.researchgate.net/profile/Teijo_ Palander/publications?sorting=newest&page=2 (accessed on 2 March 2020).
- 44. Inkinen, T.; Hämäläinen, E. Reviewing Truck Logistics: Solutions for Achieving Low Emission Road Freight Transport. *Sustainability* **2020**, *12*, 6714. [CrossRef]
- 45. European Modular Systems. 2013. Available online: http://www.modularsystem.eu/ (accessed on 2 March 2020).
- 46. DieselNet, Emission Standards. 2014. Available online: https://www.dieselnet.com/standards/eu/hd.php (accessed on 2 March 2020).
- Park, Y.S.; Lim, S.H.; Egilmez, G.; Szmerekovsky, J. Environmental efficiency assessment of U.S. transport sector: A slack-based data envelopment analysis approach. *Transp. Res. Part D Transp. Environ.* 2018, 61, 152–164. [CrossRef]
- 48. Seppänen, R.; Kervinen, M.; Parkkila, I.; Karkela, L.; Meriläinen, P. *MAOL-Tables*; Otavan kirjapaino Oy: Helsinki, Finland, 2012; p. 167. (In Finnish)
- 49. Neste, Pro Diesel Summer Quality, Tuotetiedote. 2017. Available online: https://www.neste.fi/static/ datasheet_pdf/150425_fi.pdf (accessed on 2 March 2020). (In Finnish).
- 50. Neste, Pro Diesel Winter Quality, Tuotetiedote. 2017. Available online: https://www.neste.fi/static/datasheet_pdf/150445_fi.pdf (accessed on 2 March 2020). (In Finnish).
- 51. Teboil, Diesel Summer Quality, Tuotetiedote. 2018. Available online: https://www.teboil.fi/globalassets/ tuotetiedotteet/diesel-kl.pdf (accessed on 2 March 2020). (In Finnish).
- 52. Teboil, Diesel Winter Quality, Tuotetiedote. 2018. Available online: https://www.teboil.fi/globalassets/ tuotetiedotteet/diesel--29_-38.pdf (accessed on 2 March 2020). (In Finnish).

- 53. Tuomaala, M.; Ahtila, P.; Haikonen, T.; Kalenoja, H.; Kallionpää, E.; Rantala, J.; Tuominen, P.; Shemeikka, J.; Rämä, M.; Sipilä, K.; et al. Energy efficiency measurements and potentials. *Sci. Technol.* **2012**, *1*, 1–340. (In Finnish)
- 54. Nurmi, J. Heating values of the above ground biomass of small-sized trees. *Acta For. Fenn.* **1993**, 236, 1–30. (In Finnish) [CrossRef]

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).