Woodchip transportation: Climatic and congestion influence on productivity, energy and CO2 emission of agricultural and industrial convoys

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~~Environmental analysis of~~ Woodchip transportation: climatic and congestion influence on productivity, energy and CO2 emission of agricultural and industrial convoys. ~~comparison between agricultural and industrial vehicles~~

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Abstract

Aim of this study is to analyze the energy requirements and the CO_2 emission of the wood chip transportation in a short supply chain (within a radius of the travelled distance equal to 70 km), using two different types of vehicles: agricultural and industrial convoys. Three itineraries (located in North-West of Italy) with different length (14.5, 36.5 and 68.5 km) but similar in route characteristics were travelled by both the convoys in three different traffic conditions (morning, afternoon and evening) and in two different road states (dry and wet). The energy balance was always positive (from 48 to 335) and truck values were about twice than tractor. The specific energy was directly proportional to the itinerary length and the lowest values were observed in the shortest itinerary (9.44 MJ m^{-3} for the truck and 17.19 MJ m^{-3} for the tractor). The net energy highlighted similar values for both convoys (3350 MJ m^{-3}). The CO_2 eq. emission per volume unit transported ranged from 0.94 to 8.53 kg m^{-3}, while per kilometer travelled it varied between 1.33 and 4.24 kg km^{-1}. The truck is more efficient than the tractor, especially in dry road conditions, but it was less versatile.

Keywords: biomass transport, truck, tractor, CO_2 emission, energy

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1. Introduction

The wood biomass is an interesting energy source to reduce the pollution in atmosphere, because during the burning it emits the same greenhouse gases (GHG) absorbed during its growth phase [1]. ~~In addition, in recent years, the wood biomass used for energy production~~ It has also been ~~economically~~ subsidized by some national and European policies in the recent years [2]. ~~At this regard,~~ Wood chip is therefore the most suitable wood biomass form for medium and large scale power stations, due to its energetic and economic sustainability [3-4]. Another advantage ~~in woodchip use~~ is its easy transportation: a truck can transport 100-110 bulk cubic meters of chips while it can charge only 65 stacked cubic meters of logs [5]. ~~Moreover,~~ This biofuel may be moreover economically convenient also if it is transported over long distances, whereas logs are competitive up to about 50 km [6].

Nevertheless, transport is ~~among all~~ one of the most energy intensive operations ~~involved~~ in the energy woodchip chain, ~~among the most energy intensive operations~~ both in the dedicated plantations [7-8] and in the traditional forestry provision [9]. ~~Moreover, as observed by~~ Other Authors [10-11] moreover observed that the higher global warming potentials (CO_2 eq MJ^{-1} of produced wood chips) are due to the biomass transport. Energy requirements and CO_2 emissions may be heavily reduced if ~~there~~ distances from the forestry yard to the energy plants are shorter [12]. For this reason, the policy strategies of some European countries encourage short wood fuel supply chains [13].

Railway transport may further reduce GHG emissions [14], but it is viable only if the train biomass loading points are close to the user plants, if the woodchip availability is guaranteed and if there is a good local road network around the woodchip production yards. Also in this scenario, however, the distance is the parameter mainly affecting the energy advantages [15].

From an economic point of view, the railway storage points may be useful as buffer biomass storage to supply energy wood requirements at any time [5].

Road woodchip transportation ~~can be performed~~ is accessible by industrial vehicles and agricultural tractors coupled with specific trailers [16]. The firsts are generally ~~built~~ suitable for long distances ~~use~~ [17] and their flexibility is ~~measured with~~ related to the possibility to travel forest roads and to access ~~the~~ forestry yards. Sessions et al. [18] discussed different van designs for truck configuration to transport energy wood in step terrain areas, considering different delivery systems used for comminuted wood.

Lofroth et al. [19] ~~found that~~ evaluated fuel costs ~~may reach~~ 35% of the whole timber operating costs, while Manzone and Balsari [16] observed a total cost for a road ~~train for the~~ woodchip transportation of approximately 5.11 € m^{-3} for agricultural convoys and 2.72 € m^{-3} for trucks, considering an average distance of 50 km.

Many studies were carried out to optimize and to model log transportation since the nineties [19-25], but there are few works developed on woodchip haulage [17] and they do not concern short distances [26].

Differently by many real work conditions, trucks are often considered as the most valid road transportation systems in various studies on wood biomass sustainability evaluation, especially considering the environmental impact [14, 28]. At medium short distances (50-70 km) the use of agricultural convoys (tractor plus trailer) ~~is~~ has been increasing in the woodchip transportation. This ~~choice~~ is due to their availability in the farm and to their lower hourly cost, also if their load capacity is lower than industrial convoys (truck and trailer) [16]. ~~In additions,~~ Tractors are moreover preferred ~~to the trucks~~ because their trailer may be directly load in field [29] and they may travel on bumpy roads, ~~which are frequent~~ widespread in forestry areas [30].

On the basis of these considerations, Aim of this study is to analyze the energy requirements and the CO_2 emission of the wood chip transportation in a short supply chain (within a radius of the travelled distance equal to 70 km), using two different types of vehicles (agricultural and industrial convoys) and analyzing various parameters conditioning the road transportation: road design, congestion, road surface conditions. The road design (traffic lights, intersections, roundabouts, stopping distances) heavily influences acceleration and deceleration rates of the vehicles, causing different environmental impacts (fuel consumption and travel times) [31]. Also the daytime may influence the environmental and economic sustainability of the transport operation [32] because the traffic jam may heavily affects both the emissions and fuel consumption. In addition, also The asphalt surface condition is also crucial: considering that the woodchip transport is performed especially during the autumn and winter seasons, it is important to analyze the convoy performance considering different climatic conditions (rain, sun, fog, ice) during the woodchip transportation.

For these reasons, 18 different scenarios were considered explored for each convoy: three itineraries (14.5, 36.5, and 68.5 km length), three day times (morning, afternoon, and evening) and two road conditions (dry and wet).

2. Materials and methods

2.1 Vehicles used

Tests were carried out with two different vehicle types: an agricultural and an industrial convoy. The agricultural convoy consisted in a tractor - trailer system: the agricultural tractor had a standard 4WD propulsion system (New Holland series 6-175) and it was coupled with a standard farm trailer with three axles and turning front axles placed on slewing rings trailer

(Crosetto, CMR300) (Table 1). The industrial convoy was a specific road train (truck + trailer) equipped with a light alloy body for the transport of low bulk density materials (as woodchip).

~~In detail,~~ Both the vehicles (widespread in the woodchip transportation in Italy) ~~used in this study~~ were ‘‘large volume’’: this is the usual definition when the transport vehicles are equipped with a container sized to reach the maximum volume allowed by road standards.

~~Both the machines are widespread in the woodchip transportation in Italy.~~

The agricultural trailer and the road train were equipped with standard industrial tires, at a pressure value of 6.5 bar. The agricultural tractor, instead, had conventional agricultural radial tires at a pressure of 1.3 bar.

In order to reduce the influence of the driver behavior, all vehicles were driven by drivers with at least three years of experience.

Table 1 - Technical characteristics of the vehicles used in the tests

Tractor	Agricultural	Industrial
Type	New Holland series 6-175	Iveco Stralis 260s48
Power (kW)	118	352
Mass (kg)	5900	12600
Transportable volume (m^3)	-	40
Trailer		
Type	Crosetto, CMR300	Zorzi 26R083/19R
Mass (kg)	6950	7200
Axles (n)	3	3
Transportable volume (m^3)	40	60

2.2 Itineraries ~~considered in the tests~~

The three ~~chosen~~ itineraries (located in North-West of Italy) are common travelled routes by the woodchip conveyors to reach the power station located in Airasca (TO). The itineraries have different length but they are similar in route characteristics, because the road condition influences the traffic flow [33]. Also if they are chiefly rural roads (with a width from 6.5 up to 8 meters), all the circuits are suited for both the agricultural and industrial transport, ~~with reasonable good standard,~~ not too curvy and located in flat areas without uphill and downhill. All the itineraries do not cross the villages, and beltways are present along the path. The itineraries are: A) from Villafranca Piemonte (CN) to Airasca (14.5 km); B) from Savigliano (CN) to Airasca (36.5 km); C) from Cuneo to Airasca (68.5 km). The maximum route length is ~~around~~ close to 70 km, ~~because this is~~ the limit distance for the short energy woodchip supply chain.

In all the yards both the convoys loaded the wood chip directly by the same stationary chipper (Pezzolato, PTH900), sited in a large square near the road. The unload at the power station, instead, was performed tipping the woodchip from the truck and the tractor trailers.

2.3 Scenarios

Road geometry, speed limit and route traffic volume highly influence the travel time of heavy good vehicles (HGV) [34-35]. ~~As a consequence~~ ~~The vehicles~~ HGV cannot travel at a constant speed and acceleration and deceleration rates become critical parameters, heavily influencing fuel, travel time and ~~vehicle~~ emissions [32, 36-37].

For these reasons each route was travelled by both the convoys in three different traffic conditions: early morning (high traffic volume), afternoon (medium traffic volume) and evening (low traffic volume) [34, 38] and in two different months (April and November 2015) with different road conditions. In April dry roads were almost always present, while in November wet roads, especially caused by light mist, were observed.

Three passages were surveyed for each convoy and for each traffic and road condition.

For each repetition the outward transportation was travelled at full load, while the return was accomplished with the empty containers.

The complete experimental design consisted of 108 test (Table 2).

Table 2 – Experimental design

Itinerary	Road condition	Day time	Vehicles	
			Truck	Tractor
A	dry	morning	3	3
		afternoon	3	3
		evening	3	3
	wet	morning	3	3
		afternoon	3	3
		evening	3	3
B	dry	morning	3	3
		afternoon	3	3
		evening	3	3
	wet	morning	3	3
		afternoon	3	3
		evening	3	3
C	dry	morning	3	3
		afternoon	3	3
		evening	3	3
	wet	morning	3	3
		afternoon	3	3
		evening	3	3

2.4 Travel time consumption and productivity

Each unit working time was acquired using the method proposed by Magagnotti and Spinelli [39] for the biomass chain. In detail, in this work the productive travel time was subdivided in three categories: net working time (NWT) referred to the normal travel condition (roundabouts, traffic lights, intersections), complementary working times (CWT) for the convoys load and unload, and unproductive working times (UWT) which are delays concerned unpredictable events during the biomass transportation (road-works and road accidents) [40]. A digital stopwatch (Hanhart ® Profile 5) was used to record each time element with a centesimal readability, which correspond to the measurement accuracy.

The average travel speed was calculated using the standard cinematic formula, dividing the travel distance for the travel time. Productivity was determined on the basis of a cycle level based on a roundtrip [41] and was expressed in terms of volume (m^3) per distance (km) and per hour (h). In this calculation the UWT were not considered, because their duration is unpredictable.

2.5 Energy Consumption

Energy consumption related to woodchip transport operation was calculated on the basis of the energy content of consumed fuel and lubricant (direct energy consumption) and of the energy used for machineries the machines manufacturing (indirect energy consumption) [42]. The input and output energy values of wood chips transportation were estimated multiplying the amount of different input (fuel consumption, lubricant consumptions…) by specific energy coefficients [43]. For example, the amount of energy input (MJ m^{-3}) for fuel consumption was calculated multiplying the quantity of fuel consumption for volume unit of woodchip transported (L) by the energy content on of fuel unit (MJ L^{-1}). In the present study, Direct energy inputs were determined considering an energy content of 37.0 MJ L^{-1} for fuel [44] and 83.7 MJ kg^{-1} for lubricant [45]. In addition, Fuel and lubricant equivalents were inflated with an additional energy value of 1.2 MJ kg^{-1} linked to their transportation on the territory of their distribution [46]. Machinery energy was estimated adopting using the formula of Equation 1 [47] (Eq. (1)):

$$ME = ELG / TC \qquad (1)$$

Wwhere:

ME = machine energy (MJ m^{-3}).

E = machine production energy (MJ $kg^{-1}yr^{-1}$);

L = machine useful life (year);

G = machine weight (kg)

T = machine economic life (h)

C = machine productivity (m^3 h^{-1})

~~In detail,~~ Values of production energy of the considered machines ~~in this study~~ were: 9.5 MJ $kg^{-1}yr^{-1}$ for self-propelled machines (tractors, loaders and trucks) and 7.0 MJ $kg^{-1}yr^{-1}$ for the trailers [45]. A useful life of 10,000 hours was estimated for tractors and trucks, while a service life of 3,000 hours ~~were~~ was considered for trailers and loaders. ~~In addition,~~ An annual utilisation of 1,000 hours for industrial vehicles (trucks) and 500 hours for agricultural vehicles were assumed in the energy consumption calculation [16]. Energy ~~spent~~ for maintenance and repair was ~~considered~~ 55% of the machine manufacturing energy ~~needed for~~ [48] and, for this reason, it was considered as a part of indirect energy in the energy evaluation. Fuel consumed in the woodchip transportation was measured by the "topping-off system", which consist of the machine tank refilling at the end of each travel~~. The amount of fuel necessary to fill the tank was considered as consumed for transport performing~~. A 2-litre glass pipe with 0.02-litre graduations, corresponding to the accuracy of measurements, was used to refill the tank [49]. The lubricant consumption was evaluated ~~assumed as a function~~ as 2% of the consumed fuel ~~consumption in a measure of 2%~~ [50].

~~In this studyT~~The energy efficiency of the transport operation was evaluated adopting a method used for agricultural systems: the energy balance (EB). ~~In detail, this latter~~ It was ~~calculated as~~ the ratio between the energy output (MJ m^{-3}) and the energy input (MJ m^{-3})(Eq.

(2)). Furthermore, the energy related to transport operation transportation was evaluated also trough the analysis of other energy indices: energy productivity (EP), specific energy (SE), and net energy (NE) (eq. (3-5)). The energy productivity was calculated both per volume unit (EP_v) (3a) and distance unit (EP_d)(3b).

EB = Energy Output (MJ m^{-3}) / Energy Input (MJ m^{-3}) (2)

EP_v (m^3 MJ^{-1}) = Woodchip output (m^3 h^{-1}) / Energy input (MJ h^{-1}) (3a)

EP_d (km MJ^{-1}) = Avg. forward speed (km h^{-1}) / Energy input (MJ h^{-1}) (3b)

SE (MJ m^{-3}) = Energy input (MJ h^{-1}) / Woodchip output (m^3 h^{-1}) (4)

NE (MJ m^{-3}) = Energy Output (MJ m^{-3}) - Energy Input (MJ m^{-3}) (5)

In the present study, The human labour, instead, was only expressed as manpower per unit time and not as energy [16].

2.6 Environmental assessment

The environmental impact of woodchip transportation was estimated considering both the CO_2 emission coefficient of fuel combustion during the travel (including loading and unloading operations) and machinery production (: this parameter was expressed as kg m^{-3} and kg km^{-1}). An average of 3.76 kg of CO_2 per liter of fuel [51] and an amount of 2.94 kg of CO_2 for each kg of lubricant [52] emitted in the atmosphere were assumed. In addition, The environmental impact of the maintenance was calculated considering an emission value of 0.159 kg CO_2 per MJ of energy content in the machines [53].

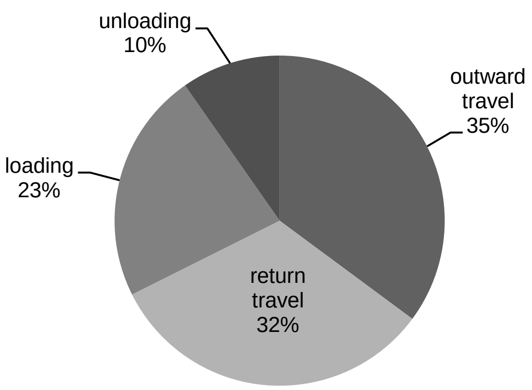
2.7 Statistical analysis

Data were processed and statistical analysis was applied using Microsoft Excel and IBM-SPSS Advanced Statistic Package, version 23. Specifically, The ANOVA test was adopted used with a significance level equal to of 0.05 and the Tukey post-hoc analysis was performed [53]; Tukey test was used because it shows an optimal power for this kind of data distribution [54].

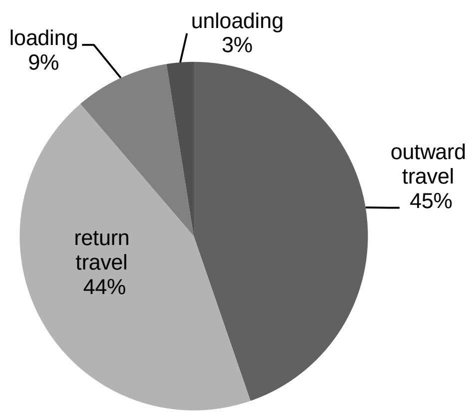
3. Results

3.1 Time consumption and productivity

Data processing highlighted that for the medium travel distance (about 35 km) the total time (including the loading and unloading operations) was 3.09 hours for the truck and 2.66 for the tractor (Fig. 1). The loading and unloading time varied in function of the convoy type because the truck and tractor trailers had different payload capacity. In our case the average loading time was of 42 and 14 minutes respectively for the truck and the tractor, while the average unloading time was 18 and 4 minutes each. The averaged recorded unproductive times (UWT) were always under the lower than 1% of the total travel time and for this reason they were included in the voyages travels.



a)



b)

Figure 1. Time consumption incidence for truck (a) and tractor (b) convoys

The average net travel time (NWT) observed during the all the tests was around 1 minute and 40 seconds per kilometer for the truck and approximately 2 minutes for the tractor (Table 3). This time is directly proportional to the distance and the difference between the vehicles increases with the itinerary length (Fig. 2).

Table 3 – Average time, forward speed, productivity and manpower

Itinerary	Road condition	Daytime	Vehicle	Round time (h)		Speed (km h^{-1})		Productivity (m^3 h^{-1})		Manpower (s m^{-3} km^{-1})	
				Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
A	Dry	Morning	Tractor	1.31	*0.04*	26.83	*0.76*	30.58	*0.93*	3.36	*0.10*
			Truck	1.05	*0.02*	33.67	*0.76*	95.25	*2.09*	1.08	*0.03*
		Afternoon	Tractor	1.19	*0.02*	29.50	*0.50*	33.69	*0.58*	3.05	*0.05*
			Truck	0.98	*0.03*	36.17	*1.26*	101.96	*3.47*	1.01	*0.04*
		Evening	Tractor	1.06	*0.06*	33.17	*1.76*	37.89	*2.00*	2.72	*0.15*
			Truck	0.87	*0.06*	41.33	*3.01*	115.25	*7.63*	0.89	*0.06*
	Wet	Morning	Tractor	1.43	*0.13*	24.67	*2.25*	28.18	*2.59*	3.67	*0.34*
			Truck	1.19	*0.03*	29.67	*0.76*	84.36	*2.07*	1.22	*0.03*
		Afternoon	Tractor	1.16	*0.06*	30.17	*1.61*	34.46	*1.82*	2.99	*0.15*
			Truck	1.09	*0.03*	32.50	*1.00*	92.14	*2.62*	1.12	*0.03*
		Evening	Tractor	1.06	*0.02*	33.00	*0.50*	37.70	*0.58*	2.73	*0.04*
			Truck	1.01	*0.06*	34.83	*2.31*	98.86	*6.37*	1.04	*0.06*
B	Dry	Morning	Tractor	2.71	*0.14*	25.50	*1.32*	14.78	*0.77*	3.54	*0.18*
			Truck	2.00	*0.12*	34.83	*2.31*	50.23	*3.16*	1.04	*0.06*
		Afternoon	Tractor	2.32	*0.10*	29.83	*1.26*	17.29	*0.72*	3.02	*0.13*
			Truck	1.82	*0.10*	38.33	*2.08*	55.04	*2.89*	0.95	*0.05*
		Evening	Tractor	2.13	*0.13*	32.50	*2.00*	18.84	*1.16*	2.78	*0.17*
			Truck	1.55	*0.06*	45.00	*1.80*	64.41	*2.60*	0.81	*0.03*
	Wet	Morning	Tractor	2.68	*0.19*	25.83	*1.89*	14.97	*1.10*	3.50	*0.25*
			Truck	2.71	*0.14*	25.50	*1.32*	36.95	*1.92*	1.41	*0.07*
		Afternoon	Tractor	2.28	*0.15*	30.33	*2.02*	17.58	*1.17*	2.98	*0.20*
			Truck	2.32	*0.10*	29.83	*1.26*	43.22	*1.81*	1.21	*0.05*
		Evening	Tractor	2.03	*0.03*	34.00	*0.50*	19.71	*0.29*	2.65	*0.04*
			Truck	2.13	*0.13*	32.50	*2.00*	47.09	*2.90*	1.11	*0.07*
C	Dry	Morning	Tractor	5.06	*0.16*	27.50	*0.87*	7.91	*0.25*	3.27	*0.10*
			Truck	3.62	*0.14*	38.67	*1.53*	27.68	*1.06*	0.94	*0.04*
		Afternoon	Tractor	4.54	*0.23*	30.67	*1.53*	8.83	*0.44*	2.94	*0.15*
			Truck	3.19	*0.10*	44.00	*1.50*	31.39	*1.02*	0.83	*0.03*
		Evening	Tractor	3.90	*0.12*	35.67	*1.15*	10.26	*0.33*	2.52	*0.08*
			Truck	2.86	*0.14*	49.33	*2.84*	35.05	*1.76*	0.74	*0.04*
	Wet	Morning	Tractor	5.00	*0.18*	27.83	*1.04*	8.01	*0.30*	3.24	*0.11*
			Truck	4.01	*0.20*	34.83	*1.89*	24.96	*1.30*	1.04	*0.05*
		Afternoon	Tractor	4.64	*0.21*	30.00	*1.32*	8.63	*0.38*	3.00	*0.14*
			Truck	3.55	*0.13*	39.33	*1.53*	28.16	*1.07*	0.92	*0.04*
		Evening	Tractor	3.92	*0.09*	35.50	*0.87*	10.21	*0.25*	2.54	*0.06*
			Truck	3.38	*0.13*	41.33	1.61	29.58	*1.12*	0.88	*0.04*

In good weather conditions (dry road) the forward speed of the agricultural tractor (30 km h^{-1}) was 25% lower than the lorry (40 km h^{-1}), but in wet road conditions this difference was only 10%. The weather conditions are more negligible for the tractor, because its allowable forward speed is always less than 40 km h^{-1}. The working time and, as a consequence, the forward speed were conditioned by the different traffic conditions observed during the day (morning, afternoon and evening). The forward speed in the worst traffic condition (morning), 33 and 26 km h^{-1} respectively for the truck and the tractor, increased of 4 km h^{-1} in the afternoon and of about 8 km h^{-1} during the evening for both the vehicles.

The average truck productivity was near 3 times the tractor, independently by the weather condition and the day time.

The manpower required for woodchip transportation was about 1 second m^{-3} km^{-1} per unit of worker (UW) for the truck and around 3 for the tractor, with slightly lower values (about 10-15%) in the evening route.

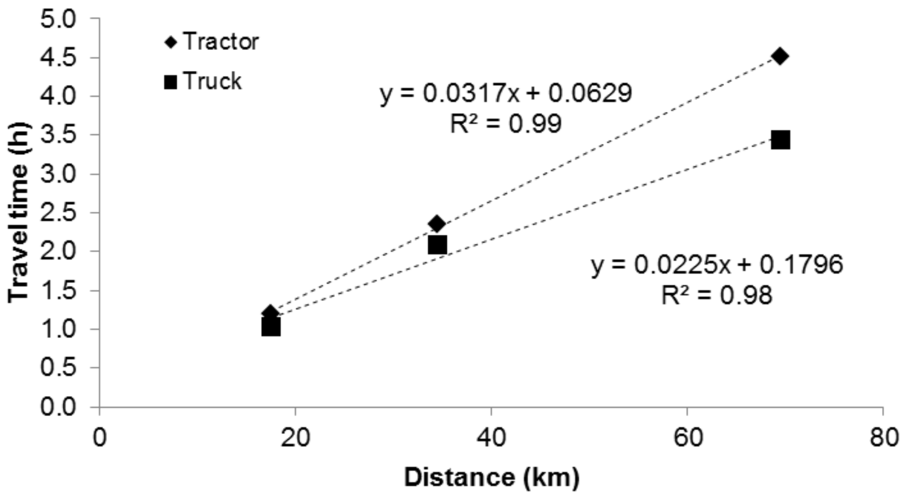


Figure 2 – Truck and tractor average travel times versus travelled distance

3.2 Energy consumption

The total energy consumption (direct + indirect ~~energy~~) ~~observed in this experimentation~~ was 37.07 MJ m^{-3} for the tractor and 20.37 MJ m^{-3} for the truck (values obtained in the itinerary B characterized by the medium length of 34.5 km). The values difference of the two vehicles ~~tested~~ (55%) was quite similar in the other two itineraries and in all ~~working~~ tested conditions ~~analysed~~.

The direct energy of the tractor ~~refereed to~~ per unit of transported volume (m^3) was always about 100% higher than the ~~of~~ truck independently from the travelled distance. In the itinerary A (14.5 km), the observed values were 12.61 and 6.76 MJ m^{-3} respectively for ~~the~~ tractor and truck, while in the itinerary C (68.5 km) they were 45.98 MJ m^{-3} and 21.80 MJ m^{-3} ~~for the truck and for the tractor~~. The direct energy consumption calculated for distance unit ~~travelled~~ was about 13.91 MJ km^{-1} for the tractor and 18.13 MJ km^{-1} for the truck. ~~These values~~ This difference (23%) is quite similar in all the working conditions (Table 4).

Table 4 – Direct and indirect energy consumptions

Itinerary	Road condition	Daytime	Vehicle	Direct energy (MJ km^{-1})		Direct energy (MJ m^{-3})		Indirect energy (MJ m^{-3})		Total energy (MJ m^{-3})	
				Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
A	Dry	Morning	Tractor	15.66	*0.47*	13.70	*0.41*	7.09	*0.22*	20.79	*0.63*
			Truck	19.66	*0.41*	6.88	*0.14*	3.52	*0.08*	10.40	*0.22*
		Afternoon	Tractor	14.26	*0.23*	12.48	*0.20*	6.44	*0.11*	18.91	*0.31*
			Truck	18.43	*0.59*	6.45	*0.21*	3.29	*0.11*	9.74	*0.32*
		Evening	Tractor	12.76	*0.64*	11.17	*0.56*	5.73	*0.30*	16.90	*0.86*
			Truck	16.44	*1.01*	5.75	*0.36*	2.92	*0.19*	8.67	*0.54*
	Wet	Morning	Tractor	17.02	*1.50*	14.89	*1.32*	7.73	*0.70*	22.63	*2.02*
			Truck	22.08	*0.52*	7.73	*0.18*	3.97	*0.10*	11.70	*0.28*
		Afternoon	Tractor	13.97	*0.69*	12.23	*0.60*	6.30	*0.32*	18.53	*0.93*
			Truck	20.29	*0.56*	7.10	*0.19*	3.64	*0.10*	10.74	*0.30*
		Evening	Tractor	12.80	*0.19*	11.20	*0.16*	5.75	*0.09*	16.95	*0.25*
			Truck	19.01	*1.13*	6.65	*0.39*	3.40	*0.21*	10.05	*0.61*
B	Dry	Morning	Tractor	16.14	*0.81*	27.84	*1.39*	14.69	*0.75*	42.53	*2.13*
			Truck	18.55	*1.10*	12.80	*0.76*	6.69	*0.41*	19.48	*1.16*

		Afternoon	Tractor	13.84	*0.57*	23.86	*0.99*	12.55	*0.53*	36.42	*1.52*
			Truck	16.95	*0.89*	11.70	*0.61*	6.10	*0.33*	17.80	*0.94*
		Evening	Tractor	12.74	*0.77*	21.97	*1.33*	11.54	*0.71*	33.51	*2.04*
			Truck	14.54	*0.58*	10.03	*0.40*	5.21	*0.21*	15.24	*0.61*
	Wet	Morning	Tractor	15.97	*1.11*	27.55	*1.92*	14.53	*1.03*	42.08	*2.95*
			Truck	25.03	*1.25*	17.27	*0.86*	9.08	*0.46*	26.35	*1.32*
		Afternoon	Tractor	13.64	*0.88*	23.52	*1.51*	12.37	*0.81*	35.89	*2.33*
			Truck	21.45	*0.89*	14.80	*0.61*	7.76	*0.33*	22.57	*0.94*
		Evening	Tractor	12.16	*0.17*	20.97	*0.31*	11.00	*0.16*	31.97	*0.46*
			Truck	19.75	*1.19*	13.63	*0.83*	7.13	*0.44*	20.76	*1.26*
C	Dry	Morning	Tractor	14.83	*0.46*	51.51	*1.57*	27.41	*0.84*	78.93	*2.41*
			Truck	16.50	*0.63*	22.93	*0.87*	12.12	*0.47*	35.05	*1.34*
		Afternoon	Tractor	13.32	*0.67*	46.29	*2.32*	24.60	*1.25*	70.89	*3.56*
			Truck	14.57	*0.47*	20.25	*0.65*	10.68	*0.35*	30.94	*1.00*
		Evening	Tractor	11.47	*0.36*	39.85	*1.24*	21.14	*0.67*	61.00	*1.91*
			Truck	13.08	*0.63*	18.19	*0.88*	9.58	*0.47*	27.76	*1.36*
	Wet	Morning	Tractor	14.66	*0.53*	50.94	*1.82*	27.10	*0.98*	78.04	*2.81*
			Truck	18.29	*0.92*	25.42	*1.27*	13.45	*0.68*	38.87	*1.95*
		Afternoon	Tractor	13.61	*0.61*	47.30	*2.11*	25.15	*1.14*	72.45	*3.25*
			Truck	16.22	*0.60*	22.54	*0.83*	11.91	*0.44*	34.45	*1.27*
		Evening	Tractor	11.51	*0.27*	40.00	*0.95*	21.23	*0.51*	61.23	*1.45*
			Truck	15.45	*0.59*	21.48	*0.81*	11.34	*0.44*	32.82	*1.25*

3.3 Energy parameters

<u>In this chapter the energy balance, the specific energy, the net energy, and the energy productivity are analysed and the results are described (Tables 5 and 6).</u>

Table 5 – Energy parameters

Itinerary	Road condition	Daytime	Vehicle	Energy balance		Specific energy (MJ m^{-3})		Net energy (MJ m^{-3})		Energy productivity (m^3 MJ^{-1})		Energy productivity (km MJ^{-1})	
				Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
A	Dry	Morning	Tractor	162.84	*4.84*	18.69	*0.56*	3363.21	*0.62*	0.05	*0.00*	0.04	*0.00*
			Truck	325.50	*6.91*	9.61	*0.20*	3373.60	*0.22*	0.10	*0.01*	0.03	*0.00*
		Afternoon	Tractor	178.96	*2.97*	17.01	*0.28*	3365.09	*0.31*	0.06	*0.00*	0.05	*0.00*
			Truck	347.73	*11.45*	9.00	*0.29*	3374.26	*0.32*	0.11	*0.00*	0.04	*0.01*
		Evening	Tractor	200.63	*10.24*	15.20	*0.77*	3367.10	*0.86*	0.07	*0.01*	0.05	*0.00*
			Truck	391.41	*24.98*	8.02	*0.50*	3375.33	*0.54*	0.12	*0.01*	0.04	*0.00*
	Wet	Morning	Tractor	150.35	*13.48*	20.34	*1.81*	3361.37	*2.02*	0.05	*0.00*	0.04	*0.00*
			Truck	289.30	*6.88*	10.81	*0.26*	3372.30	*0.28*	0.09	*0.00*	0.03	*0.00*
		Afternoon	Tractor	182.96	*9.39*	16.66	*0.83*	3365.47	*0.93*	0.06	*0.00*	0.05	*0.00*
			Truck	315.19	*8.71*	9.93	*0.27*	3373.26	*0.30*	0.10	*0.00*	0.03	*0.00*
		Evening	Tractor	199.65	*2.94*	15.25	*0.23*	3367.05	*0.25*	0.07	*0.01*	0.05	*0.00*

			Truck	337.45	*21.04*	9.30	*0.56*	3373.95	*0.61*	0.11	*0.01*	0.03	*0.01*
B	Dry	Morning	Tractor	79.70	*4.10*	38.18	*1.91*	3341.47	*2.13*	0.03	*0.00*	0.04	*0.00*
			Truck	174.11	*10.77*	17.99	*1.08*	3364.52	*1.16*	0.05	*0.01*	0.03	*0.01*
		Afternoon	Tractor	93.03	*3.84*	32.70	*1.36*	3347.58	*1.52*	0.03	*0.00*	0.05	*0.00*
			Truck	190.50	*9.84*	16.43	*0.87*	3366.20	*0.94*	0.06	*0.00*	0.04	*0.00*
		Evening	Tractor	101.24	*6.14*	30.09	*1.82*	3350.50	*2.04*	0.03	*0.01*	0.05	*0.00*
			Truck	222.25	*8.80*	14.08	*0.57*	3368.76	*0.62*	0.07	*0.00*	0.05	*0.01*
	Wet	Morning	Tractor	80.69	*5.88*	37.78	*2.65*	3341.92	*2.95*	0.03	*0.00*	0.04	*0.00*
			Truck	128.62	*6.62*	24.33	*1.22*	3357.64	*1.33*	0.04	*0.00*	0.03	*0.00*
		Afternoon	Tractor	94.56	*6.23*	32.23	*2.08*	3348.11	*2.33*	0.03	*0.00*	0.05	*0.00*
			Truck	150.13	*6.19*	20.83	*0.86*	3361.43	*0.94*	0.05	*0.00*	0.03	*0.00*
		Evening	Tractor	105.85	*1.54*	28.72	*0.42*	3352.03	*0.47*	0.03	*0.01*	0.05	*0.00*
			Truck	163.38	*9.91*	19.17	*1.17*	3363.24	*1.26*	0.05	*0.01*	0.03	*0.01*
C	Dry	Morning	Tractor	42.90	*1.33*	70.81	*2.17*	3305.07	*2.41*	0.01	*0.00*	0.04	*0.01*
			Truck	96.64	*3.64*	32.34	*1.23*	3348.95	*1.34*	0.03	*0.00*	0.04	*0.00*
		Afternoon	Tractor	47.81	*2.37*	63.61	*3.19*	3313.11	*3.56*	0.02	*0.01*	0.05	*0.00*
			Truck	109.46	*3.53*	28.55	*0.92*	3353.06	*1.00*	0.04	*0.01*	0.04	*0.01*
		Evening	Tractor	55.52	*1.77*	54.74	*1.71*	3323.01	*1.91*	0.02	*0.00*	0.06	*0.00*
			Truck	122.09	*6.07*	25.62	*1.25*	3356.24	*1.35*	0.04	*0.00*	0.05	*0.00*
	Wet	Morning	Tractor	43.40	*1.59*	70.01	*2.52*	3305.96	*2.81*	0.01	*0.00*	0.04	*0.01*
			Truck	87.21	*4.50*	35.87	*1.80*	3345.13	*1.95*	0.03	*0.00*	0.03	*0.01*
		Afternoon	Tractor	46.77	*2.06*	65.00	*2.91*	3311.55	*3.25*	0.02	*0.01*	0.05	*0.00*
			Truck	98.31	*3.68*	31.79	*1.18*	3349.55	*1.27*	0.03	*0.00*	0.04	*0.00*
		Evening	Tractor	55.29	*1.33*	54.95	*1.30*	3322.77	*1.45*	0.02	*0.00*	0.06	*0.00*
			Truck	103.20	*3.85*	30.29	*1.15*	3351.18	*1.25*	0.03	*0.00*	0.04	*0.00*

Table 6 - ANOVA of the energy parameters per itinerary, road conditions, and daytime

			Energy balance	Specific energy	Net energy	Energy productivity	Energy productivity
				MJ m^{-3}	MJ m^{-3}	m^3 MJ^{-1}	km MJ^{-1}
Itinerary (A, B, C)	Tractor	A	179.23 a	17.19 a	3364.88 a	0.06 a	0.05 a
		B	92.51 b	33.28 b	3346.93 b	0.03 b	0.05 a
		C	48.614 c	63.18 c	3313.57 c	0.02 c	0.05 a
	Truck	A	334.40 a	9.44 a	3373.78 a	0.11 a	0.03 a
		B	171.50 b	18.80 b	3363.63 b	0.05 b	0.03 a
		C	102.81 c	30.74 c	3350.68 c	0.03 c	0.04 b
Road condition (Dry, Wet)	Tractor	Dry	106.96 a	37.89 a	3341.79 a	0.04 a	0.05 a
		Wet	106.61 a	37.88 a	3341.80 a	0.04 a	0.05 a
	Truck	Dry	219.97 a	17.96 a	3364.54 b	0.06 a	0.04 a
		Wet	185.86 b	21.36 b	3360.85 b	0.06 a	0.03 b
Daytime (Morning, Afternoon, Evening)	Tractor	Morning	93.31 a	42.64 a	3336.50 a	0.03 a	0.04 a
		Afternoon	107.35 a	37.87 a	3341.82 a	0.03 a	0.05 b
		Evening	119.70 a	33.16 a	3347.08 a	0.04 b	0.05 b
	Truck	Morning	183.56 a	21.83 a	3360.36 a	0.06 a	0.03 a
		Afternoon	201.88 a	19.42 a	3362.96 a	0.06 a	0.03 a
		Evening	223.29 a	17.75 a	3364.78 a	0.07 b	0.04 b

Note: different letters indicate significant difference between treatments for α = 0.05

3.3.1 Energy balance

The calculated energy balance is always a positive number and for the truck it is about twice than the tractor. The values change in function of the itinerary; in fact, they were inversely proportional to the travelled distance (Table 5 and 6).

In detail, Considering the average values for all road conditions and daytime, the highest data were recorded in the itinerary A (14.5 km) (about 180 for the tractor and 335 for the truck), while the lowest were respectively 48 and 102 in the itinerary C (68.5 km) (Table 5).

Considering the road conditions (wet and dry), statistical analysis showed significant difference only between truck values. Truck travels in dry road conditions were more efficient (around 18%) than voyages in wet conditions: in fact, better results were recorded in the first case with a value of 220. In contrast, travelling in different daytime (morning, afternoon, and evening) significantly differences can be observed for both the vehicles tested. The best energy balance was attributable to travels carried out in evening where the traffic density was lower: in fact, in this case the values were 25% higher than in the morning.

The energy ratio between output and input related to per travelled kilometer ranged between 11.5 and 6.2 respectively for the truck and tractor in the itinerary A, and it ranged between 0.75 and 0.35 in the itinerary C. In addition, lower was the travel distance, higher was the energy balance variability, especially for the truck (Fig. 4).

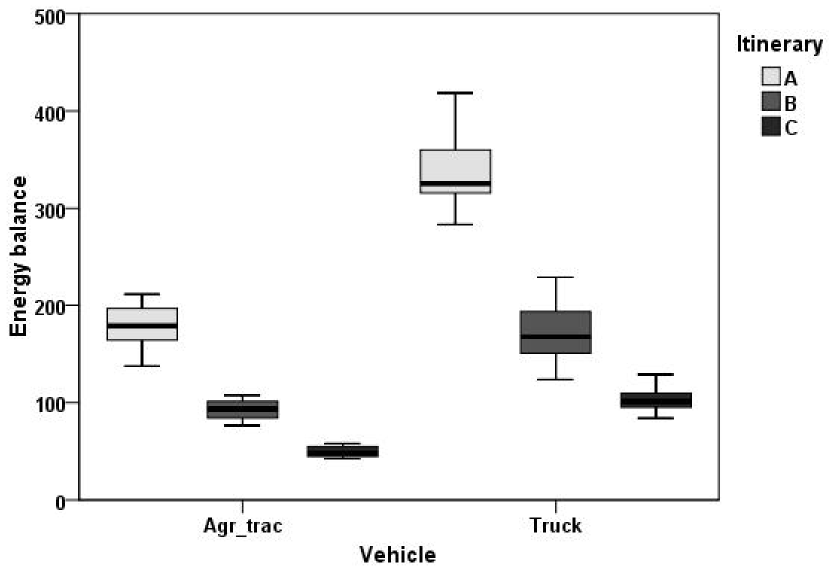


Figure 4 – Energy balance box plots of the considered vehicles on the three different itineraries

3.3.2 Specific energy

The specific energy expressed per volume unit was different in function of the travel length. Differently from the energy balance, the specific energy is directly proportional to the itinerary length (Fig. 5). The lower values were observed in the itinerary A (9.44 and 17.19 MJ m^{-3} respectively for the truck and the tractor), while the higher were recorded in the itinerary C (30.74 and 63.18 MJ m^{-3} ~~respectively for the truck and the tractor~~). In all the itineraries the difference of the specific energy between the truck and the tractor ranged from 49% to 56% and it increased in function of the distance (Tables 5 and 6).

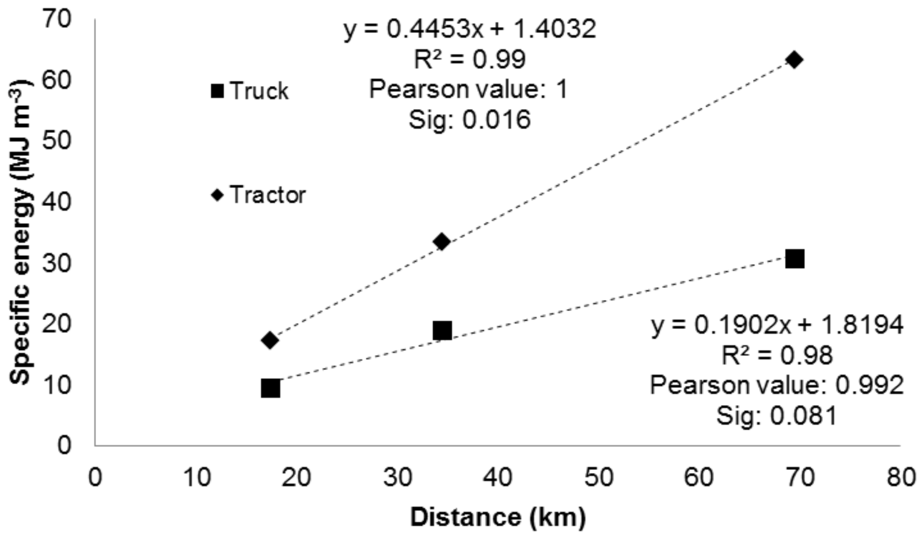


Figure 5 – Truck and tractor specific energy versus travelled distance

Similarly to the energy balance, ~~also for~~ ~~this parameter~~ the statistical analysis highlighted ~~a~~ different ~~performance~~ results in function of the road conditions only for the truck: values greater than 19% were observed in ~~dry~~ wet road conditions (Table 6). Different results emerged from the daytime analysis :a higher energetic efficiency (around 25%) was observed ~~travelling~~ in the evening route, independently by the vehicle type (Table 6).

3.3.3 Net energy

The average value of the net energy ~~calculated for all test~~ ~~resulted of~~ was about 3350 MJ m^{-3} ~~and the data showed~~ with a coefficient of variation ~~of~~ equal to 0.6%. Since the wood chip energy content is 3384 MJ m^{-3} , this value is very positive because it is 99% of the energy transported. Max and min values ranged around between ± 1% of the average value independently of the vehicle type ~~considered~~ (Table 5). Nevertheless, significant differences were observed in the three ~~different~~ itineraries ~~considered~~: a greater energy consumption is required if distance is longer (itinerary C) (Table 6). Also net energy variations are higher if distances are longer, especially for the agricultural convoy (Figure 6).

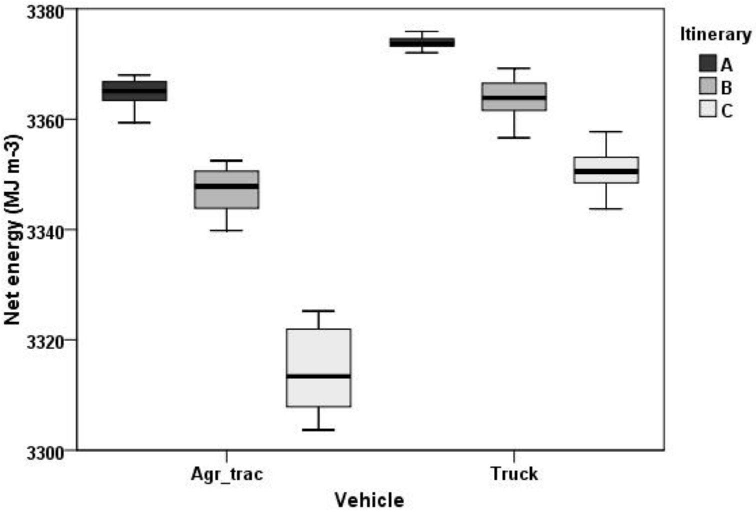


Figure 6 - Net energy box plots for the different vehicles and itineraries

3.3.4 Productivity energy

The energy productivity was different depending on the reference unit considered: transported volume (m^3) or travelled distance (km). In the first case, independently of the considered vehicles, the results of the itinerary A (14.5 km) were twice the amount calculated in itineraries B and C. Any differences were otherwise observed in the three itineraries for the energy productivity per unit travelled distance (km). Nevertheless, the tractor showed values higher more than 25% compared to the truck in all the working conditions (Table 5 and 6).

3.4 CO_2 emissions

The CO_2 eq emission per unit transported volume ranged from 0.94 to 8.53 kg m^{-3}, while it varied between 1.33 and 4.24 kg km^{-1}per travelled kilometer.

Different values were obtained in function of the vehicle type, road and traffic conditions, independently by the transported volume or the itinerary. Considering the unit volume

~~transported~~, the truck always showed values 50% less than the tractor; ~~in fact, for a~~ in the middle length itinerary (B) the truck recorded an average emission of 2.36 kg m^{-3} and the tractor 4.42 kg m^{-3}. The tractor showed otherwise lower values than the truck for the CO_2 eq. emission calculated for travelled distance unit, with an average value of 2.2 kg km^{-1} (3.0 kg km^{-1} for the truck) (Table 7).

Table 7 – CO_2 eq emission

Itinerary	Road conditions	Daytime	Vehicles	CO_2 eq emission (kg m^{-3})	CO_2 eq emission (kg km^{-1})
A	Dry	Morning	Tractor	2.21	2.52
			Truck	1.14	3.24
		Afternoon	Tractor	2.01	2.29
			Truck	1.06	3.03
		Evening	Tractor	1.78	2.04
			Truck	0.94	2.69
	Wet	Morning	Tractor	2.41	2.75
			Truck	1.28	3.66
		Afternoon	Tractor	1.96	2.24
			Truck	1.17	3.35
		Evening	Tractor	1.79	2.05
			Truck	1.10	3.14
B	Dry	Morning	Tractor	4.57	2.65
			Truck	2.16	3.13
		Afternoon	Tractor	3.91	2.27
			Truck	1.97	2.85
		Evening	Tractor	3.59	2.08
			Truck	1.68	2.44
	Wet	Morning	Tractor	4.52	2.62
			Truck	2.93	4.24
		Afternoon	Tractor	3.85	2.23
			Truck	2.51	3.63
		Evening	Tractor	3.42	1.98
			Truck	2.30	3.34
C	Dry	Morning	Tractor	8.43	2.43
			Truck	4.34	3.12
		Afternoon	Tractor	7.83	2.25
			Truck	3.84	2.76
		Evening	Tractor	4.60	1.33

		Truck	3.66	2.63
Wet	Morning	Tractor	8.53	2.46
		Truck	3.91	2.81
	Afternoon	Tractor	7.65	2.21
		Truck	3.45	2.48
	Evening	Tractor	6.58	1.89
		Truck	3.09	2.22

Nevertheless, Statistical analysis showed that only the road condition significantly influenced the CO_2 eq emission per unit of transported volume (Table 8), while any difference was found for the CO_2 eq emission per kilometer travelled, using a confidence level of α = 0.05.

Table 8 – GLM (general linear model) for CO_2 eq emissions per volume (m^3) and per distance (km) unit

	Effects	DF	SS	%	F-Value	P-Value	Power
CO_2 emission per volume unit (kg m^{-3})	Vehicle	1	114.742	6.9	327.775	<0.0001	1.000
	Itinerary	2	280.958	16.8	401.297	<0.0001	1.000
	Road condition	1	0.248	0.2	0.710	0.4021	0.132
	Daytime	2	17.727	1.1	25.319	<0.0001	1.000
	Intercept	1	1.243.860	75.1	3.553.247	<0.0001	1.000
CO_2 emission per distance unit (kg km^{-1})	Vehicle	1	17.481	2.2	406.088	<0.0001	1.000
	Itinerary	2	3.609	0.5	41.918	<0.0001	1.000
	Road condition	1	1.655	0.2	38.451	<0.0001	1.000
	Daytime	2	7.634	1.0	88.674	<0.0001	1.000
	Intercept	1	753.086	96.1	17.494.802	<0.0001	1.000

Note: confidence level of the statistical analysis α = 0.05.

4. Discussion

In general, The average forward speed of the truck (37 km h^{-1}) was always higher than the tractor (30 km h^{-1}). Concerning the speed limit permitted by the Italian traffic law (40 km h^{-1} for the agricultural machines, 70 km h^{-1} for the industrial vehicles), different performances were obtained by the tested vehicles: the tractor reached the 75% of the forward speed limit, while the truck was only at about the 53%. This is a remarkable result because in absolute terms the truck forward speed was only 7 km h^{-1} higher than the tractor. Weather and traffic conditions less influenced the agricultural convoys forward speed because it must be always less than 40 km h^{-1}. In good weather conditions the forward speed difference between the tractor and the truck was 25%, while it lowered to 10% in worst climatic situations with bad road conditions. The same trend is also observed analyzing the amount of traffic flow in the travelled rural and extra-urban roads. Also with fluid traffic conditions the maximum forward speed of trucks are effectively disadvantaged compared to agricultural vehicles because of traffic lights, roundabouts, and speed limits.

The productivity was instead very different, due to the higher truck loader capacity (100 m^3 against 40 m^3 of the tractor loader): the average truck productivity was about 3 times the tractor, independently by the weather conditions and the traffic flow. These results are in line with the values obtained in previous studies carried out on wood chip [16] and log wood transportation [56].

Concerning the time consumption related to the transport operation, data processing highlighted an high efficiency because in the analysed scenarios the unproductive times (related to roadworks and road accidents) were very low (1% of the total working time). These results were independent by the vehicle type, weather conditions, and itinerary geometry. Nevertheless, these values may become consistently higher if different traffic conditions are present or if the waiting time for the unloading at the user plant is remarkable (in some situations it may be more than 2 hours) [16].

The total energy (direct + indirect) required for the woodchip transportation with the agricultural convoy was 55% greater than the truck in all tested conditions. It is a conceivable value to the lower load capacity of the agricultural trailer (60% less than truck container).

Direct energy (fuel and lubricant consumption) per travelled kilometre was about 13.9 MJ for the agricultural convoy and 18.1 MJ for the truck. The last value is equal to Hamelinck et al. [57], while both are in line with the results obtained in other studies [58-59]. Nevertheless, it must be underlined that the direct energy per travelled kilometre depends on the different engine power of the tested vehicle, due to the correlation between fuel consumption and engine power [49], as observed in other woodchip production phases as wood chipping [60] and biomass handling [61]. ~~On the contrary~~ In opposition, the direct energy calculated per unit of volume transported was higher for the agricultural machine and was always about 100% of the industrial convoy, independently from the itinerary length. These results are ascribable to the different load capacity of the two vehicles (40 m^3 the agricultural trailer and 100 m^3 the truck plus its trailer [16].

The indirect energy contribution was about 35% of the total energy required for the transport operation of both the vehicles: this value is similar to the results obtained in biofuel transportation [62] and in wood chipping operations [60].

The energetic evaluation showed a positive value of the output input ratio (energy balance) for both the vehicles in all the investigated scenarios. This is a remarkable result because the transport operation with different convoys and with different traffic and climatic conditions does not influence the energy sustainability of the short wood chip supply chain. This logistic solution of the travelled distance within a radius equal to 70 km is strategic, because the biomass transportation is the most expensive working operation from the energetic point of view (accounting until the 80% of the total energy requirements) [63].

The weather conditions influence the energy balance only for the truck. The transportation with the truck was more efficient with dry roads because in this case its energy balance was 18% higher than the same measured in wet conditions. With different traffic flows, instead, both the vehicles showed different results: travelling in the evening (low congestion) the energy balance was 25% higher than in the morning (high congestion).

The specific energy varied only for the truck in function of the road conditions: 19% higher values were observed with wet roads. Also in this case, the congestion influenced (up to 25%) the specific energy of both tested vehicles.

Since the amount of fuel consumption is low in the different road conditions, the net energy values are directly proportional only at the itinerary length. For this reason, significant differences for both the convoys were observed only in the three itineraries and not for the different road conditions.

Similarly, also the energy productivity per volume transported showed different results only in function of the itinerary length. On the other hand, the energy productivity per unit travelled distance was equal along all the itineraries.

Analysing the energy balance, the specific energy, and the energy productivity values, the truck is more efficient than the tractor, especially in dry road conditions. Another important result of this research is the difference between the output and the input energy per unit of transported volume (net energy): it was always positive and almost equal for both the vehicles in all the tested conditions. There are not therefore differences between the agricultural and the industrial convoy for the net energy: also if the agricultural vehicle has a lower payload capacity and a lower forward speed than the truck, in the meantime it has a lower fuel and lubricant consumption.

The CO_2 eq emission analysis showed different values during the biomass transportation in function of the vehicle type. Higher results per unit of volume were observed for the tractor (4.4 kg m^{-3}) compared to the truck (2.4 kg m^{-3}), showing values 50% higher, independently by the road conditions and the traffic flow. The load capacity is mainly responsible of the different results. These values are in line with those obtained in a forest biomass supply chain study for biomass transportation [63] and in chipping operations with different type of feedstocks and machines [60]. Considering the CO_2 eq emission per unit of travelled distance, the tractor showed lower values than the truck due to the lower fuel consumption of the agricultural machines. Dry road conditions moreover permitted an average CO_2 eq reduction of about 8%, while it was further reduced to 30% when the woodchip transportation was performed in low traffic conditions (evening instead of morning). In the last case, the vehicles forward speed is more constant and there are less sudden acceleration and deceleration causing higher fuel consumptions.

Readers must also consider that there are other road constraints (maintenance, design) not analysed in this study that may influence the vehicles performance and productivity [64]. There are other important operative aspects that must be considered in the woodchip transport operation. The first is the convoy load: differently by the trucks, tractors can be used to load the woodchip directly in field, especially when self-propelled chippers are employed. This fact makes tractors more versatile than the trucks because they can work in different working conditions maintaining also a lower hourly cost [65-66]. The second aspect is the possibility to use a standard farm equipment to load the trailer of the tractor: in fact, the commonly used trucks for woodchip transportation have top sides 4 m high, only reachable with specific loader equipments (e.g. telescopic loaders) [61].

Also the agricultural vehicle availability is a main element: tractor is always available in the farm, while the truck must be rented, increasing operative times and costs. Tractor fixed costs are moreover lower than truck [67].

In conclusion, considering all the energetic and environmental parameters, the road conditions (dry and wet) influenced the results, especially for the truck: in fact, worse values were obtained in case of wet roads. These conditions must be carefully evaluated in a logistic supply plan, because the wood biomass is mainly harvested and transported during the autumn and winter seasons, when the weather conditions make the roads wet. Moreover in the logistic plan also the traffic conditions must be evaluated, because congestions may influence the forward speed of the vehicles, but in the meantime the low speed of the heavy (trucks) and slow (tractors) convoys causes the slowing down of other vehicles. The difference between the output and input energy was positive for both the vehicles. Nevertheless, the tractor is more versatile than the truck because it can be used also in field to load the trailer. In order to improve the performance of the truck, it could be interesting to adopt a specific machine able to move wood chips from the agricultural trailer to the industrial convoys, reducing the load working times.

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