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Fuel Use Reduction and Economic Savings from Optimization of Road Transportation of Coniferous Roundwood

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Abstract: One of the 10 priorities of the Green New Deal is sustainable transportation. It should be considered in the perspective of long-term ecological and economic sustainability, according to the trend of opportunities for sustainable development. The economic and environmental aspects of transportation related to the harvesting and movement of timber play a special role in the energy cost and their environmental impact per distance of raw material supply. The principles of rational and energy-efficient use of transportation equipment play a key role in the movement of raw timber. These are influenced by the availability of timber resources, limitation of vehicle payloads, reduction of energy consumption expressed in terms of reduction of fuel combustion, or current legal and road regulations for timber transportation. The paper evaluates economic and environmental factors in relation to the demand for fuels necessary for the implementation of road transportation of softwood timber. The aim of this paper was to present the current situation of the use of transportation means in the movement of bulky timber, as well as opportunities to optimize fuel consumption and CO_2 emissions, affecting the economic and environmental effects. Previous studies on fuel consumption in the transportation of roundwood indicate irrational use of vehicles. This indicates unused payload capacity increasing energy inputs expressed in fuel consumption. It has been empirically investigated that this is the result of improperly approved transport sets adapted to the material being transported. In addition, it was shown that there is a clear correlation between the vehicle payload utilization rate and economic and environmental factors. The results of this study point to the potential to increase the use of transportation vehicles for timber transportation and reduce fuel combustion and CO_2 emissions by 7–20%.

Keywords: softwoods; timber transportation; transportation means; economics; environment

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1. Introduction

Timber transportation is one of the elements of logistics management on which the efficiency of management in the forest and timber sector largely depends. Due to the current legal acts on transport policy and the provisions of highway code, it is necessary to achieve an optimum between environmental protection and economic aspects of transport. Modern forest-timber management, despite the fact that it is not directly regulated by EU legislation [1], significantly affects the fulfillment of environmental objectives [2]. The scope of sustainable management in timber harvesting and transport is presented in research manuscripts reporting large datasets that are deposited in various publicly available EU documents, including the “Green Paper on forest protection and information in the EU: preparing forests for climate change” and the European Parliament resolution of 28 April 2015 on “A new EU forestry strategy: for forests and the forest-based sector”

(2014/2223(INI)) [3,4], further developed through the introduction of new directives of 16 July 2021, “New EU Forest Strategy 2030” [5].

Timber transportation is an important issue in sustainable forest and timber management, which enforces taking measures to use forests in a way that preserves the biological structure and performs the economic functions of forests without harming other ecosystems [6]. According to the Polish PEFC PL 1003:2012 regulations, which correspond to EU directives, sustainable transport conditions must be met within forest management. This approach requires both preparation and adaptation of transport infrastructure, i.e., roads, transport routes, and bridges, which must be properly planned, built, and maintained to ensure an efficient transport system. At the same time, it is required to reduce the negative impact on the environment [7], among other things, through the decarbonization of transportation [8]. Actions taken in this regard are focused on the reduction and control of exhaust emissions and the promotion of transportation modes that use renewable energy sources as fuel [9]. Transportation issues related to timber management are important not only from the point of view of an efficient and economically viable supply of wood raw material, but also from the point of view of its impact on the environment. Timber transportation within the significantly varied availability of raw material targets both land and water deliveries. Land transport is among the most demanding and problematic transportation modes. In the group of raw material deliveries with higher value indices, road transport is dominantly preferred over rail transport for the delivery of wood paper and board raw material. This is due to the peculiarities of the transported wood sorts, especially when it comes to roundwood [10]. However, these issues are not regulated by any general regulations within the European Union. In this regard, any irregularities in the transportation of wood should be considered in light of the applicable internal regulations of the member countries [11]. In Poland, the guidelines for timber transportation and safety are contained in the Regulation of the Minister of Infrastructure dated 25 January 2018, which describes both the proper arrangement of the transported raw material and the related transport safety measures [12].

An important element in planning the transportation of timber by road is the maximum permissible gross vehicle weight (GVW) on roads. In Poland, these restrictions are defined by Article 61 § 15 of the Road Traffic Law, indicating a level of 40–42 Mg, depending on the form of vehicle combination (Polish national regulations). Taking into account the vehicle type and design, the maximum permissible volume of transported pine raw material is usually between 25 and 30 m^3 [13]. However, there are discrepancies with regard to the current legislation. They often result from the dead weight of vehicles limiting loading. The most frequently reported discrepancies involve exceeding the maximum permissible load weight [14]. Significant non-optimized underloading of transport cars is also common [15]. The reasons behind such irregularities include the varying density of timber, which depends on its type, form, and period of harvesting, which contributes to high variability in cargo weight [16–19]. In addition, the variability in timber moisture content at the point of initial loading prevents accurate determination of its weight. This often results in unknowing noncompliance with timber transportation regulations [12,20].

In European countries, there is a great deal of variability in the applicable restrictions on vehicle loading, which is due to varying permissible gross weights. Germany has a maximum permissible load weight at a level similar to that in Poland (40 Mg), with discussions underway to increase it to 44 Mg [21]. According to German business associations, such a level is already allowed in Belgium, Luxembourg, and the Czech Republic. In addition, other European countries have higher permissible gross weights for transport vehicles, such as 50 Mg in the Netherlands and 54 Mg in Denmark. In contrast, the maximum permissible gross vehicle weight in Scandinavian countries is about 60 Mg, and there are also ongoing discussions on its increase [21,22]. Such a wide variation in the levels of maximum permissible load weight and differences in the total weight of a combination of road vehicles means that discussions are underway on appropriate provisions for the permissible load capacity of vehicles. This is especially true given that exceeding the permissible outage is associated with increased fuel consumption and exhaust emissions. Therefore, the research indicates the need to analyze issues related to the optimization of timber transportation.

Studies show that a reduction in CO_2 emissions in road transportation of up to 90% compared to 1990 can be achieved by 2050 through strong fleet choices. With strong fleet modification, and if all measures reach their best potency, the most common source of CO_2 emissions in wheeled transportation—the internal combustion engine—will be reduced. The magnitude of these emissions is equal to the quantity and quality of the fuel burned. Thus, the level of emissions can fall by reducing its consumption. Therefore, the article focuses on opportunities to reduce CO_2 from road transport by evaluating optimal vehicle loading. One of the main concepts for improving supply chains is cooperation between stakeholders by increasing the efficiency of the resources they share. In the literature, one can find research papers related to vertical cooperation in the logistics industry [23,24]. Such cooperation is possible thanks to databases that allow the optimal use of transportation resources and adapt them to the distance and type of product being transported.

Both the variability of regulations and the diversity of timber load preparation require the development of proposals for the possibility of increasing the cargo volume and adapting it to vehicle payloads. The aim of this study is to identify the factors responsible for the under- or oversizing of loads in the transportation of large-sized timber. As a result of the analysis, it is expedient to identify solutions that will determine the variability of cargo volume selection of the studied timber species, and which should be implemented in practice. This will have an impact on cost optimization in the context of economic and environmental aspects of road transport. As a result, it will be possible to indicate the rationale for taking measures to reduce transport cycles by optimizing vehicle filling and taking into account environmental aspects, both locally and globally.

2. Materials and Methods

The large-size timber supplies implemented in the western part of Poland were selected as the research area undertaken. It covered the entire year of 2022. The study focused on the supply of timber from 9 Regional Directorates of the State Forests, including 233 forest districts located in the indicated region of Central Europe. The research process was carried out by analyzing the road transport of pine (*Pinus sylvestris* L.) roundwood, which dominates the domestic market. The study used source materials on the transportation of timber with a volume of more than 1 million m^3. The starting point for addressing the issue was the regulations in force in Poland that inform about the permissible maximum weight of raw timber transported from selected forest districts to timber industry customers. The use of digital tools and initiatives to support smart mobility can be a key aspect of developing smart transportation load reduction areas. Traffic reduction and loading restrictions, such as loading acceptable levels of kit preparation with multiples of 25 m^3 or 30 m^3, determine the filling of trucks. The simulation deals with the evaluation of the impact of filling for cars in the range of 25 m^3 and 30 m^3 and the assumed intermediate theoretical loading of 27 m^3 averaged pine wood. It was assumed that the loading volume can have a positive impact on traffic situations, especially at high transport density.

The article attempts to find a general solution to the problem based on statistical research. To confirm the statistics, real transportation data was initially used. Then a model based on real data was created. Therefore, the paper combines the real and modeled data to serve as data for further calculations. The research methodology adopted is intended to indicate how many transportation processes can be improved by optimizing truck loading.

This case study focuses on road transport of large-sized roundwood in accordance with Regulation 51 of the Director General of the State Forests (DGSF) of 2019 and Regulation No. 54 of the DGSF of 2020 [25,26]. The form and type of wood determines the type and maximum permissible gross weight of the vehicle combination. The type of timber adopted for the study concerned large-dimensional sorts, the dimensional range of which includes a diameter of more than 14 cm at the upper end, and a length of more than 2.5 m. According to the Polish standard PN-D-95 000, when calculating the volume of a piece of wood with a length of 3–5 m, conversion factors are used (0.61 m^3 = 1 piece), and for wood with a length of more than 5 m, each piece must be individually measured. The loading measurement of round raw material was based on timber receipts at the storage site. Measurements of the permissible weight of a vehicle combination (vehicles coupled to move on the road as a whole) [27] were obtained from the technical data sheets of vehicle combination manufacturers. When calculating the payload of the vehicle combination, regardless of the calculation method used, a pine timber load of 25 m^3 or 30 m^3 (depending on the declared equipment of the truck) was taken into account. Delivery of the raw material was carried out in accordance with the guidelines of the Road Traffic Law [27]. In this case study, the research included vehicles with a permissible load of 40 Mg, self-loading vehicles with a permissible capacity of 25 m^3, and vehicles without auxiliary equipment with a permissible capacity of 30 m^3 [28]. In relation to the actual weight of vehicle combination, their maximum permissible load of 40 Mg was assumed in further analysis. In the real world for individual companies, logistics programs are used to optimize the use of transportation means by filling them optimally. Such cooperation is simpler when the freight carrier has flexible transportation facilities. Cargo consolidation, then, can be considered crucial for low-carbon supply chain solutions. This paper evaluates loadings for 67 types of vehicles, where the problem of designing multi-carrier transportation pooling strategies in a supply chain is examined. The purpose of the paper is to examine the impact of these collaborations on CO_2 emissions reduction using a real-world event-based methodology. Using a case study of selected trucking companies, strategies for changing vehicle weight and GVW (permissible gross vehicle weight) to lower CO_2 emissions compared to a supply chain without pooling are examined.

When considering the economic and environmental transportation cost, attention was paid to two key parameters: distance and fuel consumption level. Their contribution to the total transportation cost is significant and may vary. Factors influencing the transportation cost include the price of fuel and its consumption, which depends on the optimization of vehicle utilization, vehicle travel distance, or vehicle speed.

Tables 1 and 2 provide a summary of fuel prices in Poland in 2022. Prices in euros were calculated based on exchange rates provided by the National Bank of Poland. The average price of diesel fuel for 2022 was €1.41/L [29].

Table 1. Min, max, and average prices in Poland for 12 months of 2022.

Fuel Type	E 95	E 98	Diesel	LPG
		EUR/L *		
Min	1.15	1.20	1.15	0.57
Max	1.70	1.82	1.72	0.78
Average	1.43	1.54	1.41	0.70

*—according to the average annual exchange rate of the National Bank of Poland. Source: based on [30,31].

Table 2. Average monthly diesel prices in Poland in 2022.

Diesel Price in Poland												
Months	1	2	3	4	5	6	7	8	9	10	11	12
EUR/L *	1.28	1.19	1.54	1.55	1.56	1.66	1.61	1.53	1.57	1.68	1.67	1.64

*—according to the average annual NBP exchange rate. Source: based on [30,31].

Both the vehicle's tonnage and its speed translate into average combustion, which is in the range of 24–33 L/100 km (Figure 1). For the purposes of this study, after verifying data from the prevailing transport companies in Poland, an average value of 29 L/100 km was assumed. The reduction of combustion in transport vehicles is so significant that an effort to minimize the number of transits should take into account sets of vehicles in large transport fleets. This translates not only into lower fuel consumption costs, but also into lower emissions of harmful substances and greenhouse gases into the atmosphere.

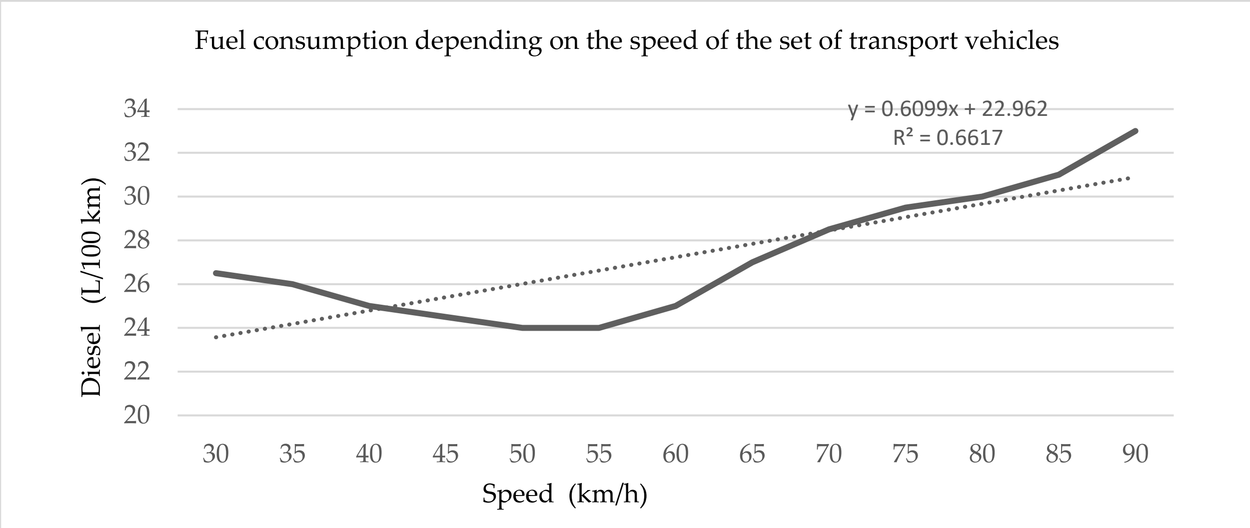

Figure 1. Combustion variability depending on the speed of movement of the vehicle combination up to 40 Mg. Source: based on [32].

The authors focused their work on the cost of fuel because:

– it represents a significant item in the operating costs of transport companies—fuel costs can account for up to approximately 30–50% of total costs,
– fuel prices in the analyzed area of the country are comparable; hence, in the presented example, it was possible to take averaged prices for calculations.

The remaining transportation costs, both variable and fixed, vary widely among the different operators and depend on many factors, such as the fleet owned (including vehicle vintage, mileage, vehicle make), wages, number of customers, or order book.

Thus, changing the weight of the goods transported significantly affects the unit cost of transportation. Transporting goods by low-capacity vehicles over long distances becomes economically unjustifiable. In order to make the transport process optimal, it is necessary to strive for maximum utilization of vehicle cubic capacity, while complying with the applicable road regulations. Such action will reduce fuel costs.

Calculations took into account both the cost of transportation fuel and the use of transportation means in relation to the allowed amount of pine wood raw material. As a result of the study, it was determined, among other things:

– percentage of deliveries on an annual basis,
– potential number of transits, depending on the vehicle payload and delivery distance for the assumed pool of 1 million m^3 of raw material,
– total CO_2 emissions achieved as a result of the distance traveled by transport vehicles with a permissible load of 40 Mg,
– estimated deviation in the weight of transported cargo,
– estimated fuel costs as a function of specific vehicle payloads.

The analyzed period was the full year of 2021, during which the vehicles were used evenly. In the course of the study, the following were determined: the distance of the loaded trip and the volume of the transported wood.

Transport vehicles were used in the area of nine designated regional directorates to transport pine raw material to timber plants over a distance in the range of 40–530 km. Based on the verified amount of 1 million cubic meters of large-size pine timber transported, the percentage of transports carried out over each distance was determined. The distances covered are presented in intervals of 10 km.

The simulation concerns the evaluation of the defined volume of vehicles only (up to 25 m^3 and up to 30 m^3). At the same time, the impact of using an intermediate fill of 27 m^3 was simulated, which can be justified in situations of vehicle overloading or carrying an incomplete load.

In the research, data was obtained from five transport companies with diverse transport sets with an indication of the actual tare weight of the vehicle combination compared to the gross vehicle weight after loading. A total of 67 types of vehicle sets were separated on this basis. The results were compiled for 37,040 transports over 49 distances with spacing every 10 km. The group included sets with the ability to load up to 25–27 m^3 of pine timber (with a regulatory density of 740 kg/m^3) and with a loading volume of 27–30 m^3 of pine timber.

The simulation of the process of utilization of transport means assumed the evaluation of the degree of utilization in sets of cars loaded with pine wood in quantities 25–27 m^3 and 27–30 m^3, in relation to the multiples of completed courses in the analyzed delivery distances.

Reference was made to the evaluation of the level of use of cars with a capacity of up to 30 m^3 of pine wood as the maximum permissible filling of a set of transport vehicles in Poland in accordance with the DMC of 40 Mg. At the same time, the simulated indirect loading was verified, increasing the actual loading volume for heavy-duty autos from 25 m^3 to a hypothetical volume of 27 m^3, and reducing the loading volume from the actual 30 m^3 to a hypothetical 27 m^3. The simulation is intended to show the effect of mass from the load on potential economic effects in the form of the cost of fuel burned, and environmental effects in the form of CO_2 emissions.

Reduction of fuel consumption is extremely important, as vehicle exhaust contains a large proportion of toxic compounds, emitted by the engine. Hence, not only the type of harmful substances matters, but also their concentration. For the environment, CO_2 is the greatest problem. The exhaust also contains other pollutants, but due to their trace amounts, they were not considered in the study. CO_2 emissions from anthropogenic sources, and therefore vehicle exhaust, contribute to the greenhouse effect. Therefore, it is important to increase the environmental awareness of the public, which affects the correct and economical operation of vehicles, and as a result carries the possibility of reducing greenhouse gas emissions. In the study, in accordance with literature data, it was assumed that 1 L of diesel generates an average of 2.68 kg of CO_2 [33,34].

Statistical Analysis

Statistical analysis was carried out to assess the differences in the effect of load capacity selection on the economic and environmental performance index between the variants of the three simulated processes. The analysis included one-way analysis of variance (ANOVA), followed by Tukey's post hoc tests. The program R was used for the calculations as a statistical system. R is available as free software under the terms of the GNU Free Software Foundation's GNU General Public License [35].

3. Results

The present study analyzed the transportation of softwood carried out by the analyzed entity during the period under consideration, using simulated deliveries for a volume of 1 million m^3 of large-size roundwood, transported to timber industry customers. For the assumed volume of transported raw material, the distances covered were also determined (Table 3).

As can be seen from Table 3, depending on the region analyzed, roundwood was transported over average distances with lengths ranging from 93 to 424 km. These deliveries occurred at the peak of demand for roundwood where the study evaluated the transportation of 1 million cubic meters of pine raw material, with the total harvest of large-size coniferous timber in Poland in the analyzed year at 15 million cubic meters [36]. This situation resulted in a maximum distance in road transport of 530 km, which referred to 0.01% of the total amount of timber transported with a noticeable downward trend. The largest amount of roundwood was transported at a distance of up to 40 km, which accounted for about 23% of the delivered volume of pine raw material.

Table 3. Distance of transported timber in 2022.

Forest Districts	Zielona Góra	Poznań	Wroc-law	Szczecin	Olsztyn	Piła	Szczecinek	Gdańsk	Toruń	In Total
Distance	**km**									
N courses (pcs)	126	302	300	733	3555	2033	2908	5127	21,956	37,040
min	310	175	300	240	80	140	130	50	40	40
mean	378	238	424	308	173	197	194	129	93	285
max	430	300	530	380	285	250	250	200	145	530
SD	35.72	40.36	58.47	40.81	45.59	30.51	31.24	55.44	30.69	144.31
V	1276	1629	3418	1665	2078	931	976	3073	942	20,825

Source: own study.

Taking into account the actual volume of raw material transported and the maximum permissible vehicle volumes of 25 m^3 and 30 m^3, and the average of 27 m^3, discrepancies are indicated, which point to overloading as well as underloading of vehicles (Tables 4 and 5).

Table 4. Weight of the vehicle combination with the timber self-loading system in 2022.

Weight of the Combination of Vehicles	GVW * (40 Mg)—Mass of the Vehicle Combination	Capacity	The Difference between the Actual Volume and the Maximum Volume of 25 m^3		The Difference between the Actual Volume and the Maximum Volume of 27 m^3	
kg	kg	m^3	m^3	%	m^3	%
22,105	17,895	24.18	−0.82	−3.27	−2.82	−10.44
21,450	18,550	25.07	0.07	0.27	−1.93	−7.16
21,000	19,000	25.68	0.68	2.70	−1.32	−4.90
20,775	19,225	25.98	0.98	3.92	−1.02	−3.78
20,650	19,350	26.15	1.15	4.59	−0.85	−3.15
20,530	19,470	26.31	1.31	5.24	−0.69	−2.55
20,500	19,500	26.35	1.35	5.41	−0.65	−2.40
20,455	19,545	26.41	1.41	5.65	−0.59	−2.18
20,300	19,700	26.62	1.62	6.49	−0.38	−1.40
20,285	19,715	26.64	1.64	6.57	−0.36	−1.33
20,190	19,810	26.77	1.77	7.08	−0.23	−0.85
19,825	20,175	27.26	2.26	9.05	0.26	0.98
19,800	20,200	27.30	2.30	9.19	0.30	1.10
19,767	20,233	27.34	2.34	9.37	0.34	1.27
19,745	20,255	27.37	2.37	9.49	0.37	1.38
19,605	20,395	27.56	2.56	10.24	0.56	2.08
19,585	20,415	27.59	2.59	10.35	0.59	2.18
19,556	20,444	27.63	2.63	10.51	0.63	2.32
19,500	20,500	27.70	2.70	10.81	0.70	2.60
19,390	20,610	27.85	2.85	11.41	0.85	3.15
19,320	20,680	27.95	2.95	11.78	0.95	3.50
19,315	20,685	27.95	2.95	11.81	0.95	3.53
19,290	20,710	27.99	2.99	11.95	0.99	3.65
19,195	20,805	28.11	3.11	12.46	1.11	4.13
19,175	20,825	28.14	3.14	12.57	1.14	4.23

Table 4. *Cont.*

Weight of the Combination of Vehicles	GVW * (40 Mg)—Mass of the Vehicle Combination	Capacity	The Difference between the Actual Volume and the Maximum Volume of 25 m^3		The Difference between the Actual Volume and the Maximum Volume of 27 m^3	
kg	**kg**	**m^3**	**m^3**	**%**	**m^3**	**%**
19,105	20,895	28.24	3.24	12.95	1.24	4.58
19,000	21,000	28.38	3.38	13.51	1.38	5.11
18,925	21,075	28.48	3.48	13.92	1.48	5.48
18,860	21,140	28.57	3.57	14.27	1.57	5.81
18,825	21,175	28.61	3.61	14.46	1.61	5.98
18,700	21,300	28.78	3.78	15.14	1.78	6.61
18,645	21,355	28.86	3.86	15.43	1.86	6.88
18,610	21,390	28.91	3.91	15.62	1.91	7.06
min	17,895.00	24.18	−0.82	−3.27	−2.82	−10.44
mean	20,243.09	27.36	2.36	9.42	0.36	1.32
max	21,390.00	28.91	3.91	15.62	1.91	7.06
V	689,352.26	1.26	1.26	20.14	1.26	17.27
DS.	830.27	1.12	1.12	4.49	1.12	4.16

Source: own study for pine wood density of 740 kg/m^3. * GVW—permissible total weight.

The distance of realized transits necessary to transport the total amount of raw material analyzed was calculated for the actual load level based on a set of data from own surveys taking into account the provisions of the Road Traffic Law and the maximum permissible volume of pine wood transported in one transit for cars with a permissible capacity of up to 30 m^3 of raw material. The analyses indicated the maximum range of deliveries based on the reported timber receipts (raw material deliveries were marked at 10 km intervals). The data came from shipping documents for deliveries of pine coniferous raw material with an assumed density of 740 kg/m^3. As transport companies use vehicles with a declared capacity in the range of 25 m^3, which are equipped with additional loading equipment (hydraulic truck crane) or without loading equipment with a standard load volume of 30 m^3 pine timber, deliveries for vehicles with two load volumes and an average value of 27 m^3 were simulated in the calculations. The results for 37,040 transports over 50 distances show the influence of raw material transport distance on the optimization of transport means utilization and the potential number of transport cycles (Figure 2).

Taking into account the average price of diesel fuel (Diesel) in 2022 at 1.41 euros and the average consumption of diesel at 29 L/100 km, the fuel costs were calculated and the indicator of optimal filling of transportation means was established to reduce fuel consumption as well as economic and environmental costs associated with CO_2 emissions (Figure 3). The number of transits required to transport 1 million cubic meters of timber was calculated from the level of data taking into account the provisions of the Road Traffic Law and regarding the maximum permissible volume of pine timber transported in a single transit. The maximum range of deliveries based on timber receipts in the following structure was indicated: A—load volume of 25 m^3; B—load volume of 27 m^3; C—load volume of 30 m^3 (deliveries at 10 km intervals). The calculation data was simulated taking into account the actual percentage of deliveries made for vehicles with the indicated load volumes, which shows the effect of load volume on the number of transport cycles. As the study shows, it is the differences in fuel costs resulting from underestimation of vehicle load volumes that account for a significant proportion of total fuel costs on an annual basis. Opportunity costs resulting from the lack of vehicle DMC utilization (Tables 6–8) in the group of analyzed load volume of 25 m^3 on a car with a capacity of up to 27 m^3 represent a total of 7.58%, and the use of cars with a DMC of up to 30 m^3 with a load volume of up to 27 m^3 represents potentially 9.96%. The highest level of these costs relates to the use of cars with a GVW capable of loading 25 m^3 with the alternative of loading pine timber on cars with a load volume of up to 30 m^3, which represents a total of 20.16% of lost fuel consumption costs. Forest districts are the counties from which the wood was imported. Scores were established to represent the supply range. This supply range represented the number of observations for ANOVA evaluation.

Table 5. Vehicle combination weight for systems without timber self-loader in 2020.

Weight of the Combination of Vehicles	GVW (40 Mg)—Mass of the Vehicle Combination	Capacity	The Difference between the Actual Volume and the Maximum Volume of 30 m^3		The Difference between the Actual Volume and the Maximum Volume of 27 m^3	
kg	kg	m^3	m^3	%	m^3	%
18,425	21,575	29.16	−0.84	−2.82	2.16	7.98
18,400	21,600	29.19	−0.81	−2.70	2.19	8.11
18,330	21,670	29.28	−0.72	−2.39	2.28	8.46
18,300	21,700	29.32	−0.68	−2.25	2.32	8.61
18,300	21,700	29.32	−0.68	−2.25	2.32	8.61
17,950	22,050	29.80	−0.20	−0.68	2.80	10.36
17,700	22,300	30.14	0.14	0.45	3.14	11.61
17,690	22,310	30.15	0.15	0.50	3.15	11.66
17,585	22,415	30.29	0.29	0.97	3.29	12.19
17,465	22,535	30.45	0.45	1.51	3.45	12.79
17,460	22,540	30.46	0.46	1.53	3.46	12.81
17,200	22,800	30.81	0.81	2.70	3.81	14.11
17,130	22,870	30.91	0.91	3.02	3.91	14.46
16,995	23,005	31.09	1.09	3.63	4.09	15.14
16,790	23,210	31.36	1.36	4.55	4.36	16.17
16,685	23,315	31.51	1.51	5.02	4.51	16.69
16,500	23,500	31.76	1.76	5.86	4.76	17.62
16,305	23,695	32.02	2.02	6.73	5.02	18.59
16,210	23,790	32.15	2.15	7.16	5.15	19.07
16,020	23,980	32.41	2.41	8.02	5.41	20.02
15,960	24,040	32.49	2.49	8.29	5.49	20.32
15,480	24,520	33.14	3.14	10.45	6.14	22.72
15,390	24,610	33.26	3.26	10.86	6.26	23.17
15,375	24,625	33.28	3.28	10.92	6.28	23.25
15,220	24,780	33.49	3.49	11.62	6.49	24.02
15,150	24,850	33.58	3.58	11.94	6.58	24.37
15,075	24,925	33.68	3.68	12.27	6.68	24.75
14,336	25,664	34.68	4.68	15.60	7.68	28.45
13,805	26,195	35.40	5.40	18.00	8.40	31.11
13,400	26,600	35.95	5.95	19.82	8.95	33.13
13,280	26,720	36.11	6.11	20.36	9.11	33.73
13,098	26,902	36.35	6.35	21.18	9.35	34.64
11,763	28,237	38.16	8.16	27.19	11.16	41.33
11,350	28,650	38.72	8.72	29.05	11.72	43.39
min	21,575.00	29.16	−0.84	−2.82	2.16	7.98
mean	23,937.59	32.35	2.35	7.83	5.35	19.81
max	28,650.00	38.72	8.72	29.05	11.72	43.39
V	3,588,422.24	6.55	6.55	72.81	6.55	89.89
DS.	1894.31	2.56	2.56	8.53	2.56	9.48

Source: own study for pine wood density of 740 kg/m^3. * GVW—permissible total weight.

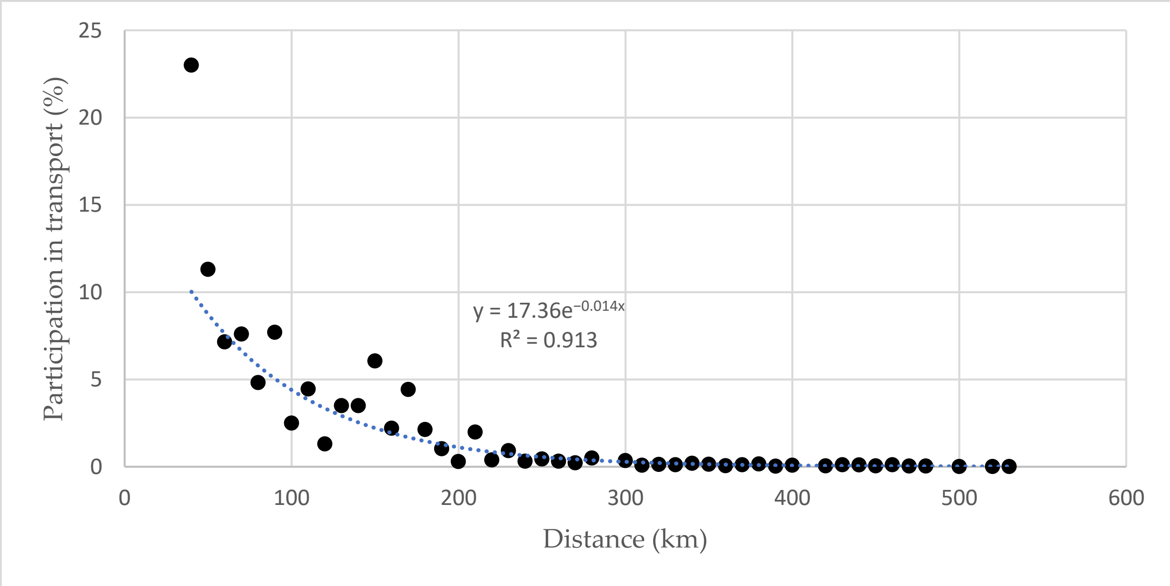

Figure 2. Distribution for the distance of transported timber in 2022. Source: own study.

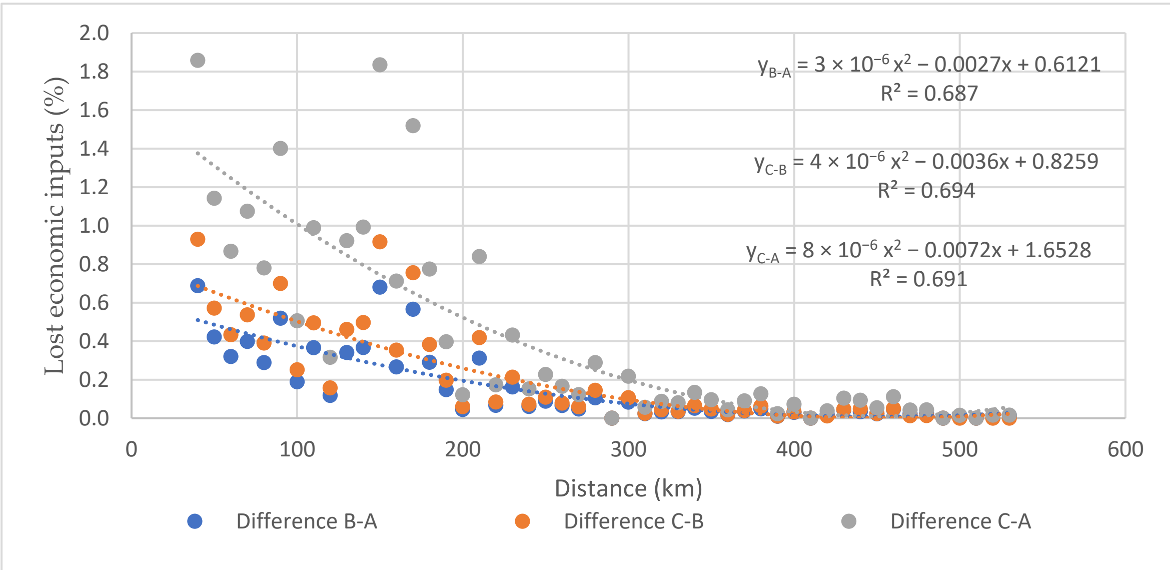

Figure 3. Distribution of the costs of lost profits in the transport of 1 million m^3 of raw material for the tested distances in 2022. Source: own study. A—vehicles up to 25 m^3; B—vehicles up to 27 m^3; C—vehicles up to 30 m^3.

Statistical analysis of the studied dependences of actual and potential financial measures to reduce fuel costs indicates the significance of the factor of vehicle combination selection in the evaluation of distance covered. Verification with the ANOVA test indicates a significant dependence of fuel cost on the loading weight of vehicles (Table 6).

The results obtained allow for statistical evaluation of the impact of load volume of road transport vehicle combinations with an average combustion of 29 L/100 km and a price per liter of diesel of 1.41 EUR, which provides an average of 40.89 EUR for a distance of 100 km in the analyzed year 2022 (Table 8).

Table 6. Effect of ANOVA of process selection size on log transport ($p < 0.05$).

Summary of Data				
	Process Variant			
	A	**B**	**C**	**Total**
$\sum X$	3,245,537	2,999,628	2,700,915	8,946,080
Mean	64,910	59,992	54,018	59,640
$\sum X^2$	540,295,660,987	462,833,969,644	374,988,987,709	1,378,118,618,340
Std. Dev.	82,018.59	75,980.47	68,376.23	75,287.79
Result Details				
Source	**SS**	**df**	**MS**	
Between variants	2,975,425,436.89	2	1,487,712,718.44	F = 0.25986
Within variants	841,594,210,460.44	147	5,725,130,683.40	
Total	844,569,635,897.33	149		

"SS"—Variability, "df"—number of independent results, and "MS"—intergroup variance.

The established F-ratio value is 0.25986. The result is significant at $p < 0.05$ level. Tukey's HSD (honestly significant difference) procedure, on the other hand, involves pairwise comparisons within ANOVA data. The F statistic indicates that there is an overall difference between the sample averages. Tukey's HSD test identifies that there is a difference between pairs of transportation test averages B and C and a slight level of difference between A and B. In contrast, there is a significant difference for pair A and C (Table 7).

Table 7. Pairwise comparisons of transport process variants with Tukey's test.

Pair		$\mathbf{HSD_{0.05} = 35{,}829.8536}$	$\mathbf{Q_{0.05} = 3.3484}$
A:B	Ma = 64,910.74 Mb = 59,992.56	4918.18	Q = 0.46
A:C	Ma = 64,910.74 Mc = 54,018.30	10,892.44	Q = 1.02
B:C	Mb = 59,992.56 Mc = 54,018.30	5974.26	Q = 0.56

Table 8. The impact of the choice of means of transport on the average level of fuel costs (diesel fuel = 1.41 EUR/l).

Fuel Cost One Curses		**Number of Transport Courses**			**Cost Transport**			**Difference**			**Difference**		
		A 25 m^3	**B 27 m^3**	**C 30 m^3**	**A 25 m^3**	**B 27 m^3**	**C 30 m^3**	**B–A**	**C–B**	**C–A**	**B–A**	**C–B**	**C–A**
EUR			**pcs**			**EUR**			**EUR**			**%**	
Sum		40,000	37,013	33,316	3,245,537	2,999,625	2,700,915	−245,912	−298,710	−544,622	7.58	9.96	20.16
mean	233.07	800	740	666	64,911	59,992	54,018	−4918	−5974	−10,892	0.15	0.20	0.40
max	433.43	9200	8518	7666	300,950	278,641	250,770	−22,309	−27,870	−50,180	0.69	0.93	1.86
DS.	118.02	1572	1456	1310	81,194	75,217	67,689	5978	7528	13,505	0.18	0.25	0.50
V	13,927.69	2,473,835	2,120,903	1,717,774	6,592,517,403	5,657,572,914	4,581,803,007	35,738,606	56,673,160	182,397,912	0.03	0.06	0.25

Source: own study.

From the environmental point of view, an important parameter in addition to the amount of fuel consumption, and therefore the cost of this fuel, is the level of CO_2 emissions and the possibility of its reduction. Table 9 summarizes the differences in diesel consumption that result from the load method of the considered types of transport vehicles, as well as the impact of such measures on CO_2 reduction.

Table 9. The level of CO_2 emission and its reduction depending on the selection of vehicle sets (emission of 2.68 kg of CO_2 with 1 L of diesel fuel).

Diesel Consumption	Diesel Fuel Consumption per Transport of 1 Million m^3 of Pine Wood (L)			Difference Diesel Consumption Reduction (L)			Difference CO_2 Emission Reduction (kg)		
	A 25 m^3	B 27 m^3	C 30 m^3	B–A	C–B	C–A	B–A	C–B	C–A
25 L/100 km	1,984,310	1,833,960	1,651,330	150,350	182,630	332,980	402,938	489,448	892,386
29 L/100 km	2,301,800	2,127,394	1,915,543	174,406	211,851	386,257	467,408	567,760	1,035,168
33 L/100 km	2,619,289	2,420,827	2,179,756	198,462	241,072	439,534	531,878	646,072	1,177,950
Difference %							7.1	9.9	20.2

Source: own study.

The CO_2 reduction results from taking into account the reduction in transportation cycles. It translates into an actual reduction in the amount of fossil fuels consumed in the road transportation process, and at the same time reduces harmful CO_2 emissions into the atmosphere (Table 9). The reduction value is based on the level of combustion quality and, according to the demand distribution, with diesel consumption in the range of 25–33 L per 100 km, can represent a CO_2 reduction of 7–20%. Such a significant amount of reduced CO_2 (from 402,938 to 1,177,950 kg of CO_2) applies to the transportation of 1 million m^3 of wood raw material, depending on combustion, i.e., 25 or 33 L/100 km, which is an average of 29 L/100 km.

4. Discussion

The study on the supply of coniferous raw material to timber plants in western Poland determined the structure of full-load transports related to the periodic demand of these entities for wood. This structure is a consequence of changes in production intensity, which characterize the periodicity of market demand for wood products. At the same time, the scale of deliveries is due to the rationality of harvesting and preparing wood for collection on road vehicles. Increased deliveries in the area closely located from timber plants reflect a reasonable tendency to reduce the movement of large-sized timber. This is due, among other things, to the transportation costs, but also to frequent inspections on the roads, which as a result of detected irregularities in relation to the current regulations, end in fines [12,37]. When analyzing the transportation of roundwood, attention should be paid to the maximum permissible gross vehicle weight (GVW). With regard to the differences that exist between the countries of the European Union, an important aspect is the discussion of a maximum load for road transport and its adjustment to the actual DMC of transport vehicles [38,39]. In the transport process, there are conditions for verification of the actual load of vehicles transporting wood with an apparent density exceeding the values specified in standardized tables. The apparent density of pine wood varies over the course of a growing year and depending on the process of natural drying, as indirectly demonstrated in the paper and confirmed in the literature [17,19]. The identified small proportion of vehicles declaring excess weight may indicate a slight overloading of vehicles loading up to 30 m^3 of raw material, and a significant proportion of non-filling of declared vehicles, which is a violation of the utilization optimization of road transport in accordance with current regulations. With regard to the demand of wood plants for raw material, it was observed that the structure of road deliveries was determined by the dominant percentage of deliveries from the area up to 90 km, which is about 62%.

The actual results obtained in this study indicate that the DMC of vehicles transporting pine timber is less than the permissible use. On the other hand, from the economic point of view, just as from the environmental point of view, it is advisable to fully utilize the maximum permissible gross weight of vehicles transporting roundwood, which may affect a smaller number of transits with a lower total environmental cost.

However, it should be emphasized that despite the significant advantages of using the vehicle DMC, this solution is not always used in practice, among other things due to the availability of prepared raw material in the receiving areas of forest districts. Nonetheless, efforts to optimize the fulfilment of wheel transportation means suggest that reducing fuel consumption is a realistic goal for the freight sector [40]. However, changes in DMC may have limitations triggered by Commission Regulation (EU) 2019/318 of 19 February 2019 [41] amending Regulation (EU) 2017/2400 [42] and Directive 2007/46/EC of the European Parliament and of the Council [43] to CO_2 emission levels of 15% by 2025 and 30% by 2030 [5]. The regulation provides for gradual reductions in fuel consumption by heavy-duty vehicles. The 2019/2020 emissions were used as the baseline [44].

The change in the maximum permissible load for road transport should be accompanied by a review of the actual weight of vehicle combinations and the volume of wood raw material types used. As a result, it will be possible to reduce both the number of loads through the achieved DMC maximum permissible weight and reduce the range of wheeled transport. Increased maximum permissible weight of vehicle combination, as is the case in other European countries, may also have a positive effect on reducing the transportation costs of wood raw material. All these optimization measures contribute to reducing the carbon footprint at various stages of the supply chain. They can also support the sustainability of supply chain development and the sustainability policies of participating companies.

In the transportation sector, sustainability is based on an analysis of its environmental impact through the sector's consumption of fossil fuels and CO_2 emissions. According to ICCT (International Council on Clean Transportation) data, the average fuel consumption of trucks between 2000 and 2015 was around 36 L/100 km. This indicates that in recent years, there has been an effort to reduce fuel consumption to an average of 29 L/100 km, which is specifically addressed in this study [45,46]. It has been assumed that loading volume can have a positive impact on traffic situations, especially when transport density is high.

Hence, there is a need for a system to supervise loading and unloading times in real time. In this study, a solution is developed to the movements resulting from the possibility of loading raw material during the release hours of the Forest Service, which significantly limits the flexible control of traffic congestion. The system used in the transportation of roundwood is based on the need to maintain the continuity of production of wood plants and require real-time traffic, such as the shift work of enterprises. Using the collected data, decision support for road availability can be developed. Traffic volumes can be evaluated using fuzzy logic for users, thereby increasing transparency in mobility operations and reducing transportation costs and times [47].

5. Conclusions

It has been shown that under Polish conditions of wheeled transport of pine raw material, the maximum distance realized was 530 km, and the dominant distance (for 62% of recipients) was up to 90 km.

The distance over which the raw material is transported depends on the supplier and the destination of deliveries. The procedure used to maximize the loading of transportation means should take into account environmental costs. Increased loading weights from 25 m^3 to 27 m^3 and borderline to 30 m^3 allows for a reduction in the number of trips of 7–16%.

Reducing fuel consumption and consequently reducing CO_2 emissions in transportation can improve the efficiency of vehicle use in the delivery process. Increasing vehicle payload capacity translates into a reduction in the number of trips and the total cost of fuel consumption. A limitation on the use of vehicles is the permissible gross weight of a set of vehicles.

Increasing the GVW of a vehicle can positively affect the actual reduction in fuel consumption and CO_2 emissions. In the case analyzed for the wheeled transport of pine raw material, decreases in fuel (ON) costs can reach from 7% to 20%.

Maximum utilization of the cargo volume of transport vehicles can be achieved by improving the organization of the process of preparing wood raw material for transport. The storage of multiples of the volume of a single load at pick-up points in individual forest districts can be an element of optimizing the use of transport vehicles and a solution for reducing fuel costs and CO_2 emissions.

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