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AXLE LOAD ON ROUNDWOOD TRUCK TRANSPORT UNIT IN RELATION TO LOAD, SET TYPE, SEASON AND GROSS VEHICLE WEIGHT

In round wood transport, high variability of transported assortments, made of different tree species, and variability of wood moisture content do not allow to clearly determine the weight of transported raw material. This affects the exceeding gross vehicle weight (GVW) of the transport unit above the legal limit. With significant GVW exceeding, forest roads are exposed to high tonnage vehicles, which results in vehicle axle loads above the accepted design parameters for the pavement and cause faster degradation of the forest roads. The purpose of this study was to investigate the real axle loads of roundwood transport vehicles arising from the gross vehicle weight (GVW) of the transport unit in different seasons of the year and depending on the type of transport set and the type of wood assortments. Measurements of axle loads for round wood truck transport units were carried out on the sites of three large wood industry companies from the north of Poland, which process different types of wood. The load on the individual axles of high tonnage truck units was measured using Model DINI ARGEO WWSD portable truck scales with a 3590M309 weighing terminal with 0.01 t graduation. In total, measurements were taken for 904 round wood deliveries, made by different transport units. Dominated was truck and trailer set with 473 deliveries, including 344 deliveries by six-axle sets. The second most frequently observed was truck and semi-trailer, 334 deliveries, where 193 was made by six-axle sets. There is a decrease in the use of truck and dolly and truck and lightweight semi-trailer combinations, which were five-axle combinations, for round wood deliveries. The lowest axle load for all sets occurs on axle one in the range of average values of 7.07-7.86t with a spread of results from 4.49 to 10.20t. The highest average axle loads of 9.15-12.43t were found on axle two for all observed transport sets, where a maximum value of 14.52t was also found. There were statistically significant differences in the values of loads on individual axles depending on the

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type of truck unit, type of wood assortment and delivery date. The distribution of the total gross vehicle weight of the set is on average 58-60% to the truck (three axles) and 40-42% to the trailer/semi-trailer (two axles) in five-axle sets, and in six-axle sets the truck and trailer/semi-trailer (three axles).

Keywords: wood transport, gross vehicle weight GVW, timber deliveries, axle overload, forest truck.

Introduction

Round wood transportation is one of the key operations in forestry and wood supply chain management, which is important in the cost of harvesting [McDonald et al. 2010; Devlin and McDonnell 2009; Delvin et al. 2008; Greulich 2002]. Wood transport is the most expensive process of obtaining the round wood and may constitute 40%–60% of the total harvesting costs [Shaffer and Stuart 1998, 2005; El Hachemi et al. 2013]. High variability of transported assortments, species variability, and varied moisture content of wood do not allow to unequivocally determine the weight of transported raw material [Koirala et al. 2017; Hamsley et al. 2007; Tymendorf and Trzciński 2020]. This very often affects the excess gross vehicle weight of the transport over the legal limit [Brown 2008; Ghaffariyan et al. 2013; Owusu-Ababio and Schmitt 2015; Trzciński et al. 2017 and 2018]. Currently, in many countries the permissible gross vehicle weights (GVW) of transport units have been raised to 60t or 76t, or even to 92t, in order to improve the efficiency of round wood transport. [Lukason et al. 2011; Sosa et al. 2015; Palander et al. 2020; Pålsson et al. 2017; Väätäinen et al. 2020; Liimatainen et al. 2020].

Wheel load and contact pressure cause temporary deformation of both the forest road surface and substructure [Martin et al. 1999; Varin and Saarenketo 2014]. Under contact pressure, forest roads are damaged, which may, after some time, make them completely impracticable due to damage from wheel overloading [Öztürk and Sentürk 2009; Martin et al. 1999]. Determination of the road load involves a quantitative and qualitative analysis of the moving vehicles. On this basis, it is possible to obtain the data necessary to determine the axle load equivalence factors [AASHTO 1993; Martin et al. 1999; Hajek 1995; Šušnjar et al. 2011a; Owusu-Ababio and Schmitt 2015; Judycki 2011]. Vehicles with a higher number of equivalent standard axles have an increased impact on the road surface. Many researchers have been concerned with the determination of traffic and its structure resulting from the purpose and types of vehicles operating on forest roads, but there are few publications on the axle loads of wood transport unit.

One of the main factors influencing the gross vehicle weight (GVW) and axle load of wood transport units is the legislation [Trzciński and Tymendorf 2017; Liimatainen and Nykänen 2017; Palander et al. 2017; McKinnon 2005]. An important element in this respect are the legal limits associated with the permissible gross vehicle weight (GVW). The European Union Member States adopted Directive 96/53/EC in 1996, setting vehicle weights of 40 Mg and 44 Mg, single axle loads of 100 kN and double axle loads of 160 kN [Directive EU 2015]. In EU countries, public transport and highway authorities have the power to limit GVW with the possibility of limiting allowable axle loads or increasing them from those specified in EU legislation, while designating roads for such vehicles, as described above. In Table 1, for selected European countries with leading forest management the permissible maximum weights in selected countries are presented.

Table 1. Weight per axle and permissible maximum weights of lorries in selected European countries

Kraj	Weight per axle [tonnes]		Permissible maximum weights of lorries [tonnes][1]						
			Road train 5 axles	Articulated vehicle 5 axles	Articulated vehicles with an increased number of axles				
	nondrive	drive			6	7	8	9	11
Austria	10.0	11.5	40	44					
Croatia	10.0	11.5	40	44					
Denmark[2]	10.0	11.5	44	44	50	56			
Finland[3]	10.0	11.5	44	44	56	60	68	76	92[4]
Germany	10.0	11.5	40	40					
Ireland	10.0	11.5	42	44	46				
Italy	12.0	12.0	44	44					
Netheralnds	10.0	11.5	50	50					
Norway[2]	10.0	11.5	46-47	40	50 60[5]				
Portugal[2]	10.0	12.0	44	44 (60)[6]					
Sweden[3]	10.0	11.5	40	44	56	60	68	74	92[7]

[1] [ITF 2019] https://www.itf-oecd.org/sites/default/files/docs/weights-2019.pdf

[2] Under specific conditions EMS (European Modular System) combinations may have a maximum length of 25.25 m and maximum weight of 60 t.

[3] Finland and Sweden are piloting even longer and heavier vehicles, with maximum weight of up to 104 t and maximum length of up to 34.5 m [Liimatainen et al. 2020]

[4] Palander et al. 220

[5] timber transport between 19.5 m and 24 m with an overall wheelbase of at least 19 m

[6] 60 t is allowed under specific conditions: transportation of woody material, paper, wood paper and ceramic products.

[7] Asmoarp et al. 2018

In Poland, there are also regulations limiting the permissible total gross vehicle weight (GVW) of vehicle transport unit on the road, which depends on the number of axles and their drive. The GVW consists of the weight of empty vehicle units and the weight of the load [Act… 2016; Act… 2012]. The transport unit should meet the requirements specified in §3 of the Regulation of the Minister of Infrastructure of 31 December 2002 on technical conditions of vehicles and the scope of their necessary equipment [Regulation...2002]. In Poland, the GVW for five-axle or six-axle sets is 40 tonnes, and the axle load depends on several factors: whether it is a drive axle, whether it is a double/triple axle, and the distance between the component axles (Table 2) [Regulation...2002].

Table 2. Permissible axle load for transport sets in Poland

Axle set	Permissible load for axle or axle unit [t]			
single axle not drive	10			
single drive axle	11.5			
Distances (d) between the component axles [m]	d<1.0	1.0≤d <1.3	1.3≤ d < 1.8	1.8 ≤ d
double axle trailers and semi-trailers	11	16	18	20
double drive axle	11.5	16	18 (19)	
two axles of engine vehicles, where one component axle is a driving axle	11.5	16		
Distances (d) between the component axles [m]	d<1.3	1.3 < d ≤ 1.4	1.4 ≤ d < 1.8	
triple axle trailers and semi-trailers	21	24	27	
three axles of engine vehicles, where one component axle is a driving axle	21	24	27	

Based on the Regulation …. 2002

One significant change in the law for wood transport was the introduction of the definition of the weight of a load of wood as the multiplication of its volume by its normative density in the Road Traffic Law [art.15 and 16 Act …2012] and on this basis issued the Regulation of the Minister of Environment and the Minister of Economy of 2 May 2012 [Regulation …2012]. This means that, given a known empty weight of the transport unit, the driver can take and the forester can release such a volume of wood that, after converting cubic meters into the weight of the load in kilograms, the total gross vehicle weight of the transport unit and the axle loads do not exceed the legal limit (e.g. 740 kg/m^3 for pine). With a GVW of 40t and an average empty weight of the transport set of 14.9-20.5t [Trzciński et al. 2018] the load weight should be in the range 19.5t to 25.1t and the real figures are much higher, GVW (gross vehicle weight) 46.0-51.5t, incl. load weight 30.3-30.9t [Trzciński et al. 2018; Tymendorf and Trzciński 2020; Kozakiewicz et al. 2021].

Research conducted into wood transport issues must take into account many factors, often specific to each country. With such large GVW, this means that forest roads are exposed to vehicles with high tonnage, often exceeding the allowable GVW, resulting in vehicle axle loads above the accepted design parameters of 10t [Czerniak et al. 2013] and is causing faster degradation of the forest road.

The aim of this study was to investigate the real axle loads of roundwood transport vehicles based on the gross vehicle weight (GVW) in different seasons of the year and depending on the type of set (truck and trailer, truck and semi-trailer, truck and dolly) and load wood assortment (large-size, sawlogs, medium-size). It was assumed that the main factor determining the axle load is GVW, the configuration of the wood transport units and its axles, as well as the assortment of transported wood.

Materials and methods

Measurements of axle loads for wood transporting units were taken at three large wood processing plants in the north of Poland, which purchase different types of wood. During the whole study period there was a sawmill of a furniture plant receiving large-size wood (mainly sawlogs) and in the period 2009/2010 additionally there was a pulp mill receiving medium-size wood (industrial wood); in 2018/2019 a particle board plant also received medium-size wood (industrial wood). Randomly selected transport units that carried wood from the forest to the mentioned facilities during the study were examined.

Transporting truck units were divided by truck and trailer arrangement and trailer type into: truck and trailer (TT), truck and semi-trailer (TS), truck and dolly (TD), truck and lightweight semi-trailer (TP) [Trzciński et al. 2013 and 2018], and number of axles in the set (five-axle and six-axle).

Large-size wood was assimilated to the round wood with a thin end minimum diameter of 14 cm (excluding bark), calculated in single pieces. In terms of quality and size, large-size wood is divided into four classes A, B, C, D and into two sub-classes, namely general-purpose wood and special-purpose wood [PN-93/D-02002; Regulation No 51]. The large-size general-purpose wood is comparable to the assortment defined as sawmill wood. Medium-size round wood (industrial wood) is the wood with a minimum diameter of at least 5cm (excluding bark), with a thick end diameter of up to 24 cm, calculated in single pieces, in pieces as groups and in piles [PN-93/D-02002; Regulation No 51]. The transport was performed by external companies acting on behalf of the processing plant. Characteristics of transported wood load (assortment): large-size (Ls), sawlogs (Sw) and its length (Sw 3.7; Sw4.0; Sw4.4; Sw5.0; Sw8.4; Sw8.8), medium-size (Ms) were determined on the basis of a delivery note issued by the State Forest District to the carrier, which is shown to the buyer and verified by him.

The gross weight of the truck unit (GVW) expressed in Mg is understood as the actual weight of the vehicle and trailer or truck unit and semi-trailer with all the equipment, the driver and round wood load. GVW was determined based on weighing the entire truck unit on a stationary scale at the factory at the moment the wood raw material was delivered.

The load on the individual axles of high tonnage truck units was measured using Model DINI ARGEO WWSD portable truck scales with a 3590M309 weighing terminal with 0.01t graduation. The scale system used is fully compliant with Polish regulations and allows vehicles in transit to be weighed. The loads on the individual wheel axles were measured successively for the whole unit: the vehicle and the trailer. The analysed GVW was also determined based on weighing the vehicle on a weighbridge, and not on the sum of the load on individual axles. The weigh station was selected in such a way it maintained a level road scale, so that the measured axles were kept leveled. The method of weighing vehicles used by the Polish Road Transport Inspectorate, which oversees compliance with permissible axle loads, assumes that measurements are taken with platform scales embedded in the surface, or by placing pads under unweighted axles, while maintaining a maximum allowed slope of 2%. The analysis was based on the results of measurements, taking into account a 5% allowable measurement error in accordance with the recommendations of the Polish Road Transport Inspectorate.

The obtained results were analysed statistically with the use of the STATISTICA 12 package. The overall results were divided into four groups related to the selected seasons (two/three-day field trips during which measurements were taken). In all analysed periods, the distributions of the variables for all parameters deviate from the normal distribution. Therefore, the significance of differences was mainly determined using the Mann–Whitney test for two independent variables, as well as the Kruskal–Wallis test, and Dunn's multi-sample rank mean comparison test (significance level was 0.05). To evaluate the relationship between the axle loads of a transport unit and its GVW (determined from a stationary scale), the Spearman correlation coefficient (Spearman's rank correlation test) was used. For the statistical tests Kruskal-Wallis, Dunn and Manna-Whitney were not taken for some of the observations groups (e.g. type of vehicle, or delivery date) due to the low number of results in a specific group (less than 15).

Results

In total, measurements were made for 904 wood transports made with different transport units (Table 3), with the highest number of 379 measurements in the year 2016 and 377 in the years 2009/2010. In the analyzed transports, truck and trailer sets dominate in the number of 473, including six-axle sets with 344 observations. The second most frequently observed transport set, with 334 observations, was the truck and semi-trailer, where six-axle sets dominate (193 measurements). There is a decline in the use of truck and dolly and truck and lightweight semi-trailer sets, which were five-axle sets, for wood transports.

Table. 3. Overview of research material collected

Truck unit	Number of axle	Number of measurements performed			Total
Year of measurements		2009/2010	2016	2018/2019	
Truck and trailer	5	63	47	19	129
	6	132	136	76	344
Truck and semi-trailer	5	72	52	17	141
	6	42	115	36	193
Truck and dolly	5	68	17	---	85
Truck and lightweight semi-trailer	5	--	12	----	12
Total		377	379	148	904

The transport units analyzed had average GVW ranging from 45.99t with a standard deviation (SD) of 2.22 (five-axle TP set) to 51.08t (with SD = 3.22) for truck and trailer (six-axle) (Table 4). The spread of registered GVW results from the stationary scale is significant from a minimum of 33.58t to 64.20t for TT - five-axle sets (Table 4). In all observed deliveries (904), almost 50% of the GVW results fall in the range from Q1 (first quartile) to Q3 (third quartile), that is, from 44.50-49.25t to 46.50-53.05t.

Table 4. Characteristics of the gross vehicle weight of the transport sets

Truck unit	Number of axles	GVW (t) Mean	SD	Min	Max	Q_1	Median	Q_3
TS	five-axle	49.13	3.98	34.42	59.94	46.80	49.62	51.52
	six-axle	50.40	2.62	42.28	57.05	48.95	50.45	51.80
TT	five-axle	49.05	4.22	33.58	64.20	46.85	49.25	51.22
	six-axle	51.08	3.22	39.58	60.00	49.25	51.15	53.05
TD	five-axle	49.99	3.85	40.06	59.64	46.78	50.18	52.85
TP	five-axle	45.99	2.22	43.60	51.65	44.50	45.85	46.50

Characteristics of axle loads

The basic statistics characterizing the axle loads of the vehicle units are presented in Table 3. Preliminary comparative analysis by Kruskal-Wallis test of all axle load results depending on the vehicle types, number of axles showed statistically significant differences. This led to the decision to present the results separately for 5- and 6-axle sets and vehicle type (Table 5). The lowest axle load for all transport sets occurs on the first axle in the range of mean values 7.07-7.86t with a spread of results from 4.49 to 10.20t. The highest average axle loads of 9.15-12.43t were found on axle two for all the test sets where the maximum value of 14.52t was also found.

Table 5. Basic statistical characteristics of axle loads

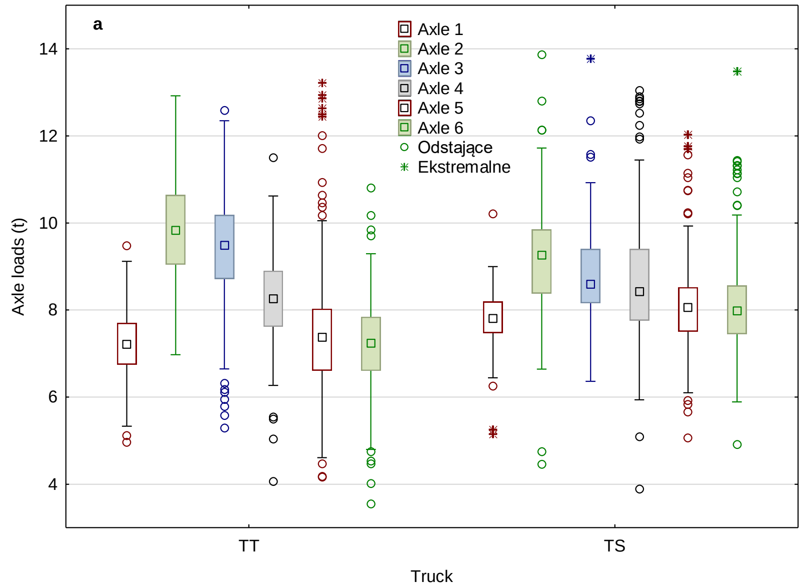
Truck unit	Number of axles	Axle	Axle load values (t) Mean	SD	Min	Max	Q_1	Median	Q_3
Truck and semi-trailer	five-axle[1]	1	7.73	0.59	5.77	8.91	7.35	7.81	8.13
		2	10.79	0.98	7.39	13.19	10.45	10.74	11.30
		3	9.90	1.43	3.75	12.54	9.07	9.97	10.91
		4	9.70	1.63	5.76	13.90	8.50	9.96	10.58
		5	9.66	1.52	5.80	13.69	8.44	9.48	10.53
	six-axle[1]	1	7.81	0.62	5.15	10.20	7.48	7.80	8.19
		2	9.15	1.25	4.46	13.87	8.38	9.26	9.85
		3	8.74	1.11	6.37	13.78	8.16	8.59	9.41
		4	8.67	1.44	5.10	13.04	7.76	8.43	9.41
		5	8.15	1.07	5.06	12.03	7.51	8.06	8.52
		6	8.11	1.17	4.91	13.48	7.45	7.98	8.56
Truck and trailer	five-axle[1]	1	7.36	1.01	4.49	9.46	6.68	7.55	8.08
		2	10.63	1.46	7.33	14.52	9.57	10.93	11.46
		3	9.93	1.43	6.95	13.40	8.81	10.05	10.73
		4	10.02	1.67	5.99	14.11	8.94	9.97	11.13
		5	9.98	1.87	3.99	14.38	8.90	10.33	11.32
	six-axle[1]	1	7.21	0.71	4.96	9.47	6.75	7.22	7.70
		2	9.89	1.17	6.97	12.92	9.04	9.83	10.64
		3	9.42	1.22	5.29	12.59	8.71	9.49	10.18
		4	8.27	0.96	4.07	11.50	7.62	8.27	8.90
		5	7.42	1.35	4.16	13.22	6.61	7.38	8.02
		6	7.21	1.01	3.29	10.81	6.61	7.24	7.84
Truck and dolly	five-axle[1]	1	7.86	0.58	6.54	8.98	7.55	7.89	8.19
		2	11.02	1.05	8.19	13.05	10.47	11.16	11.75
		3	10.58	1.17	6.19	12.73	10.00	10.73	11.37
		4	10.19	1.62	7.06	14.31	8.89	10.06	11.53
		5	10.20	1.25	8.03	13.01	9.21	10.03	11.16
Truck and lightweight semi-trailer	five-axle[2]	1	7.07	0.69	5.42	8.02	6.94	7.24	7.29
		2	12.43	0.86	10.82	14.02	11.94	12.59	12.85
		3	8.30	0.85	7.13	10.61	7.65	8.24	8.65
		4	8.17	0.84	7.08	10.27	7.51	8.19	8.49
		5	7.97	0.87	7.05	10.36	7.32	7.84	8.31

Notes: SD - standard deviation, Q_1 - first quartile, Q_3 - third quartile [1]axle 1-3 truck, [2] axle 1-2 truck

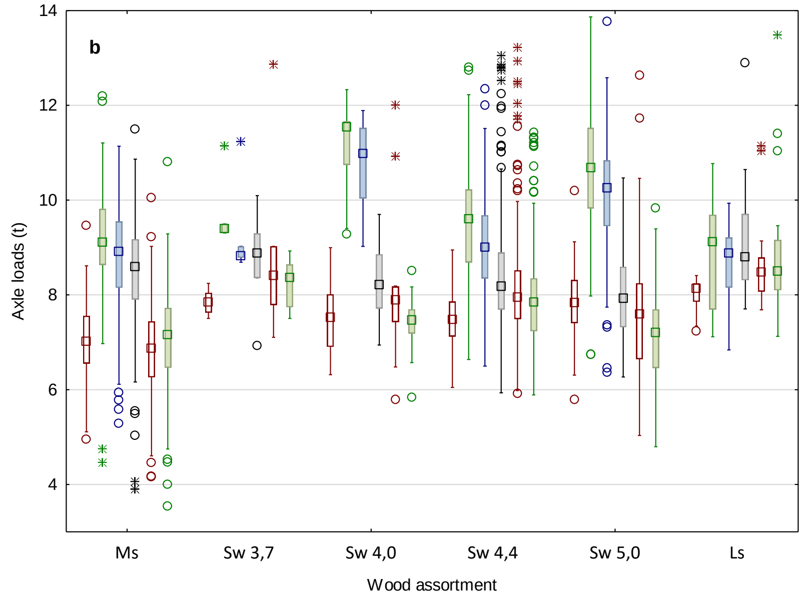
Analysis of the axle loads of the transport set depending on the investigated parameter

As already mentioned, the six-axle sets were TT and TS (Table 3 and 5) and the comparative analysis (Kruskal Wallis test) of individual axle loads between those units showed statistically significant differences (Fig. 1a). After analyzing the axle loads in relation to the transported wood assortment, it can be concluded that there are also statistically significant differences (Fig. 1b). Statistical analysis showed that there were no significant differences in axle loads for axle 1 (p=0.7549) and axle 4 (p=0.1436) depending on the delivery date, while for the other axles the differences were significant (Fig. 1c).

a)



b)



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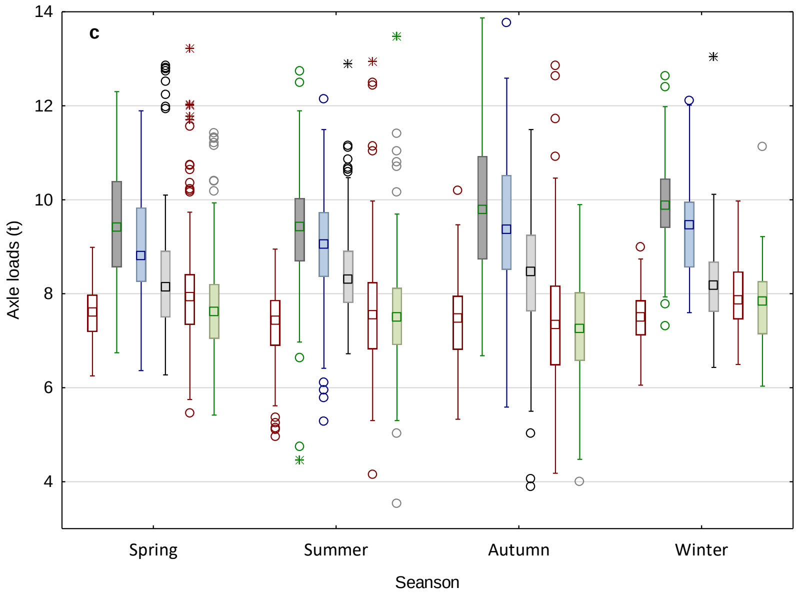


Fig. 1. Distribution of axle loads in six-axle transport sets according to: a) transport set, b) wood assortment, c) delivery date

The differences in load on the individual axles of the transport units can be seen more clearly by carrying out an analysis separately for TT and TS depending on the transported assortment (Fig. 2). In the case of TS transport sets there is no big difference between the axle loads, only in the case of short assortment Ms the second and third axle have higher average axle loads of just over 10t (Fig. 2b). In the truck and trailer combinations the highest average axle loads are on the fourth and fifth axle in the range 8.5-12.0t, with lower values for shorter 3.7m and Ms grades.

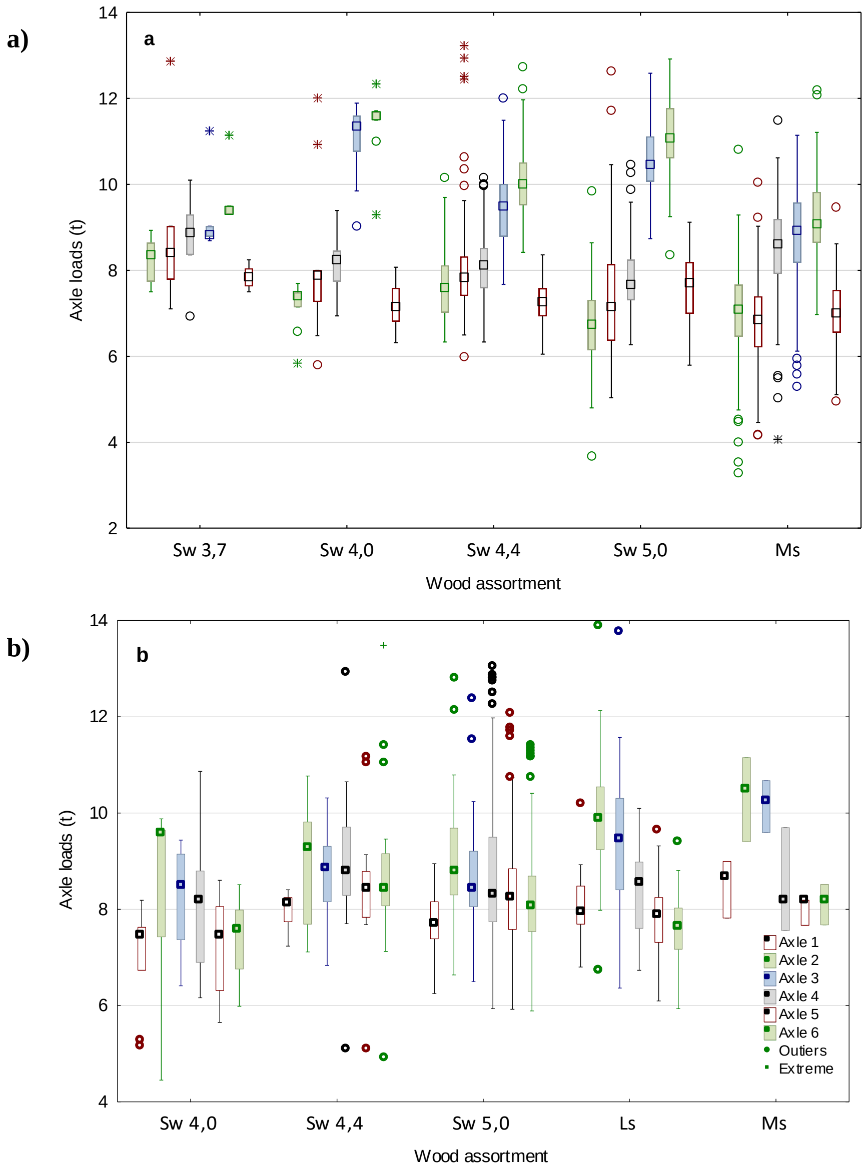
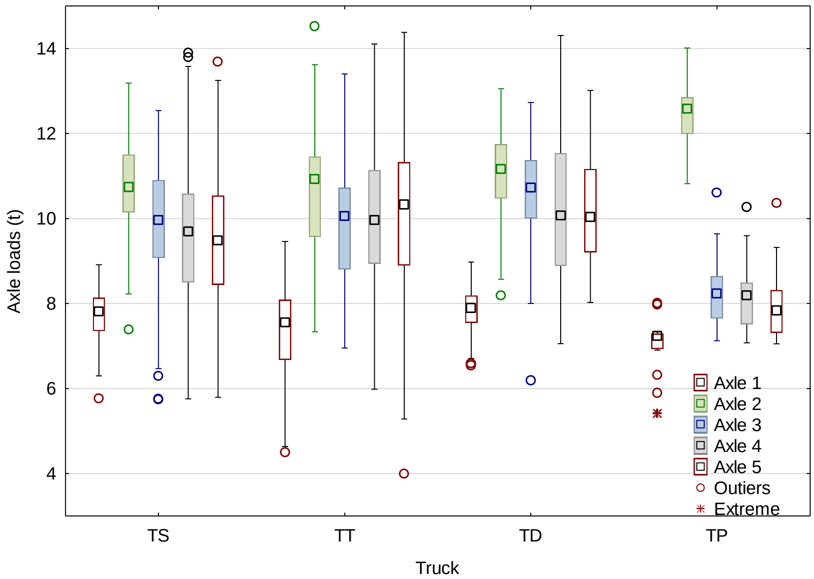


Fig. 2. Axle loads on six-axle sets depending on the wood assortment: a) truck and trailer, b) truck and semi-trailer

Five-axle sets are present in all transport unit combinations analyzed (TT, TS, TD, and TP) and influence the axle loads present. The differences in axle loads occurring are statistically significant (Kruskal Wallis test), and the test of multiple comparisons of mean ranks shows mainly differences between truck and lightweight TP and the other sets for axles two to five (Fig. 3a). The loads of transported wood (assortments) also influence the resulting axle loads, which was confirmed by statistical analysis (Fig. 3b). Sawlogs of 3.7m and 8.8m (Sw 3.7 and Sw 8.8) were excluded from the analysis due to the small sample of observations (7 and 8). For most axles there are differences in axle loads for units with Ms deliveries and the other assortments. Additionally on axles 4-5 there are differences between Ls (large-size) deliveries and the other deliveries (multiple mean rank test). Analyzing the axle loads in five-axle sets with respect to the delivery date, statistically significant differences were found for all axles. These differences occur mainly for measurements performed in summer and other seasons, most visible on the second and third axle (Fig. 3c).

a)



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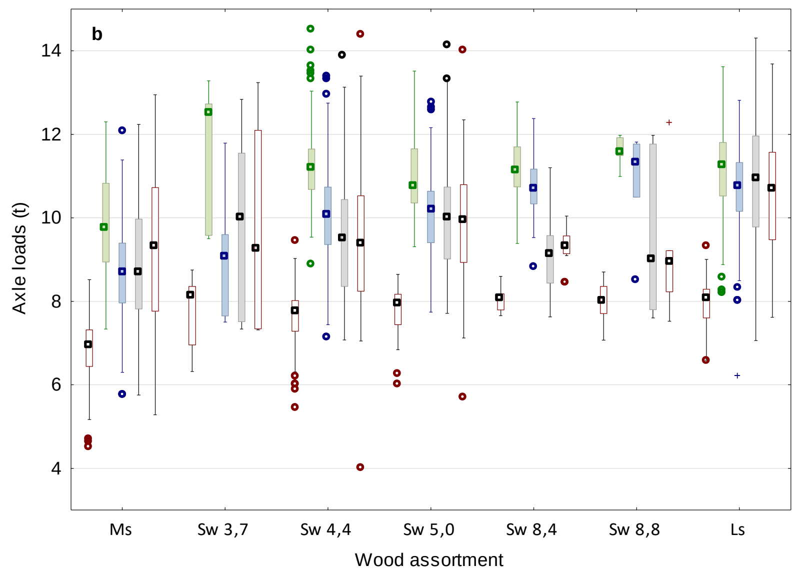

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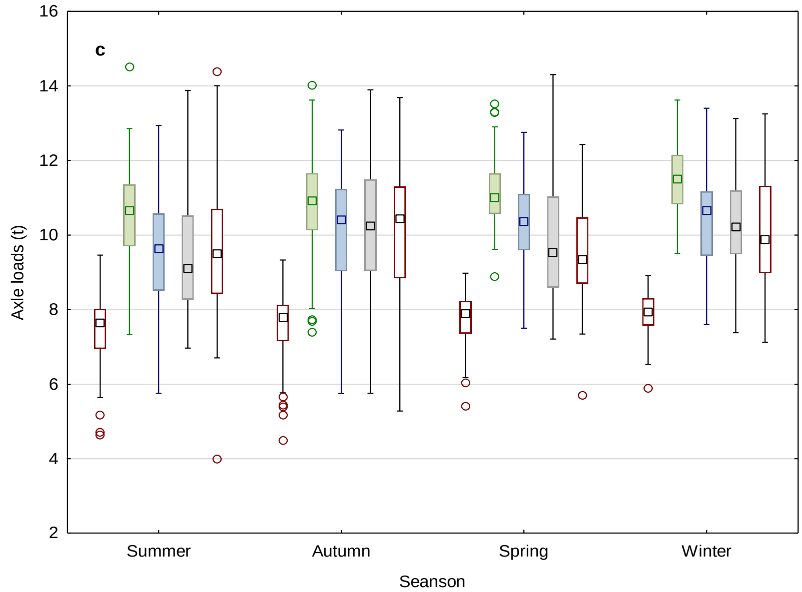
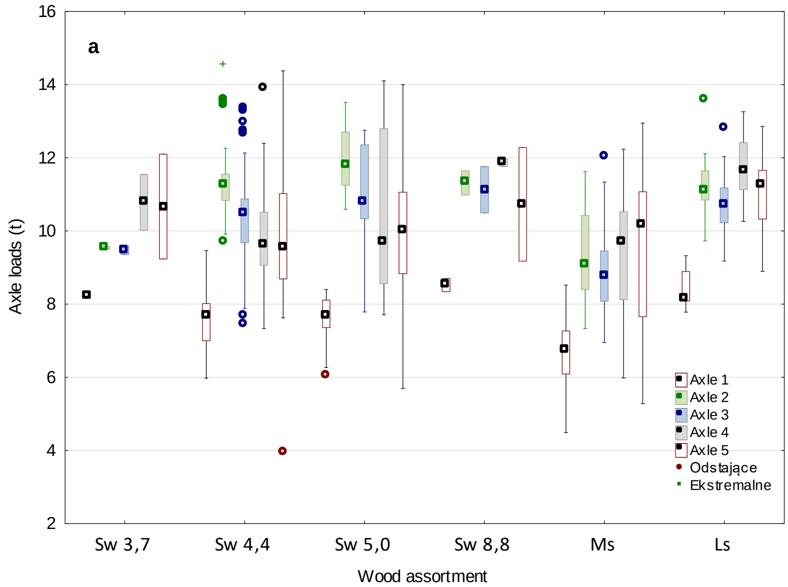


Fig. 3. Distribution of axle loads in five-axle transport sets according to: a) transport set, b) wood assortment, c) delivery date

As in the case of the six-axle sets, not every wood assortment was transported with all types of sets in the five-axle sets. In these sets, this is more evident for TD and TP, therefore an analysis of axle loads for individual units depending on the wood assortments in the load is also presented (Fig. 4). In the group of five-axle truck and trailer sets, as opposed to six-axle sets, there is also a unit with an extendable trailer, which makes it possible to transport longer loads (Ls and Sw 8.8m) (Fig. 4a). When transporting large-size timber (Ls) for TT, TS and TD sets, the first axle has the lowest average loads of 8t, while the other axles (3-5) average between 10.5-12.0t.

a)



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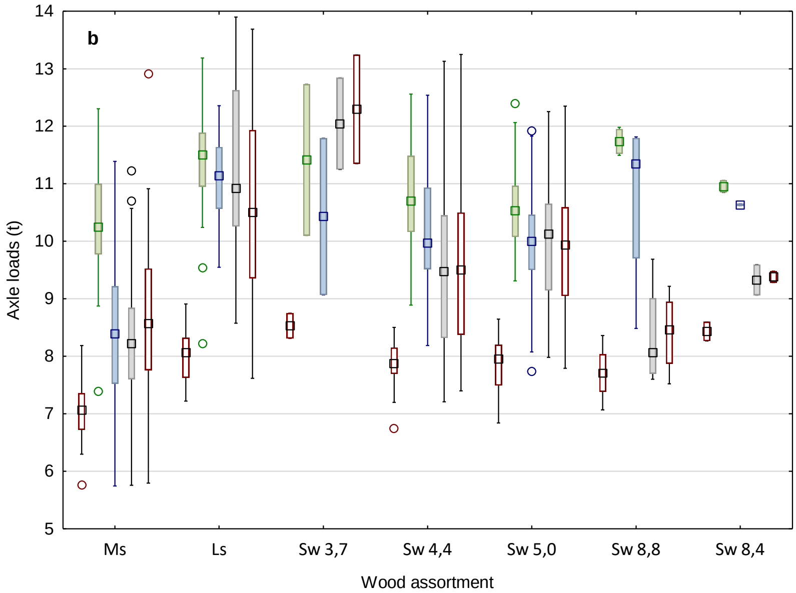

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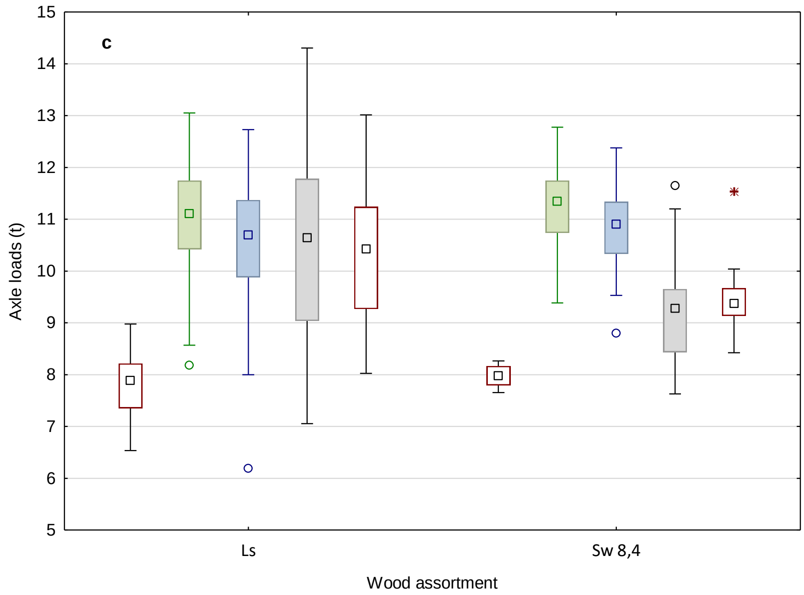

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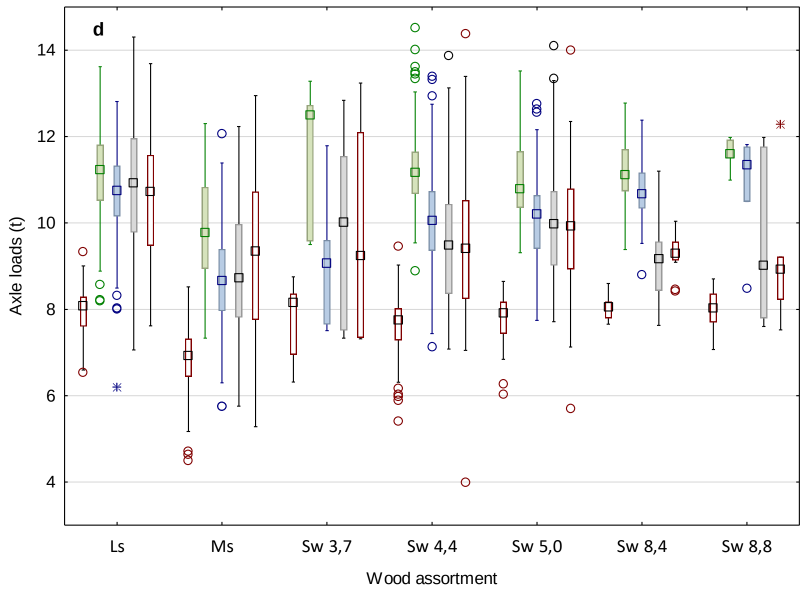


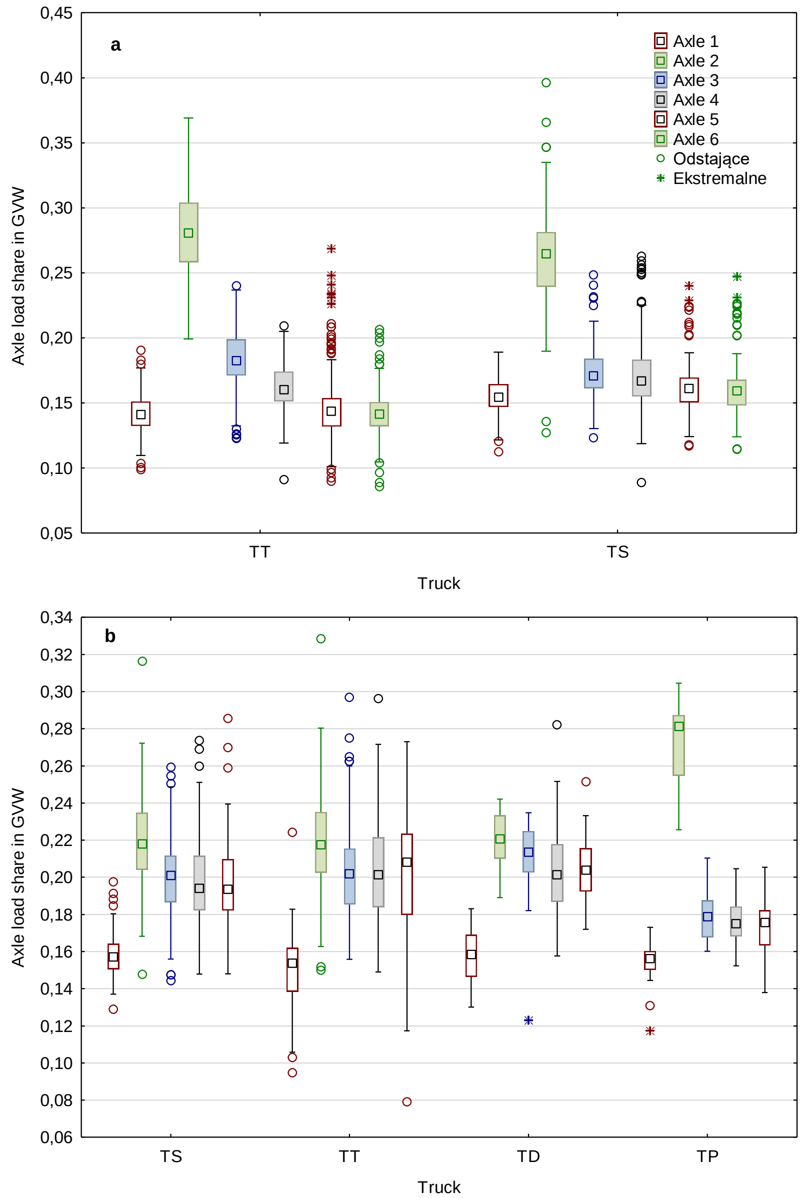
Fig. 4. Axle loads on five-axle sets depending on the wood assortment: a) truck and trailer, b) truck and semi-trailer, c) truck and dolly, d) truck and lightweight semi-trailer.

Distribution of gross vehicle weight among the axles

In six-axle combinations, on average almost 0.30 of the GVW falls on the second axle with a range of results of 0.13-0.40 (Fig.5a). The smallest share on average of 0.14-0.15 in GVW goes to the first axle with a range of results of 0.09-0.19. In six-axle combinations, the distribution of axles is even, with three axles per truck and trailer/semi-trailer. However, the mass per truck is on average 0.60 GVW (observed range 0.40-0.80) and per trailer/semi-trailer 0.46 with a range of results 0.33-0.72. The comparative analysis performed with the Mann-Whitney test confirmed that there are statistically significant differences between the six-axle TT and TS sets in the distribution of GVW per truck and trailer/semi-trailer and individual axles.

The axle distribution for the five-axle TT, TS and TD sets is the same, where three axles are on the truck and two on the trailer/semi-trailer or dolly, and for the TP set vice versa three axles truck and two axles lightweight semi-trailer. In the TP five-axle set, the distribution of GVW per axle differs significantly from the others, with a large average contribution of 0.28 to the GVW of the second axle (Fig.5b). In the other units TT, TS, and TD, the first axle averages about 0.16 GVW and the other axles each average 0.19-0.22 GVW. In the TT, TS and TD (3+2 axles) sets, there is an average of 0.58 GVW per truck (observed range 0.44-0.85) and an average of 0.40 GVW per trailer/semi-trailer or dolly (with a range of 0.27-0.54). The TP averages are: 0.42 GVW per truck (observed 0.38-0.46) and 0.53 GVW (with a range of 0.48-0.62) per lightweight semi-trailer. The distributions of GVW per truck and trailer and per axle for the five-axle combinations are statistically significantly different (Kruskal-Wallis test). Dunn's multi-sample rank mean comparison test showed no statistical differences in truck load between TT and TS ($p=0.9284$), TD and TP ($p=0.8028$) and TS and TD ($p=0.0794$), and for the trailer only between TD and TS ($p=0.0751$).

a)



b)

Fig.5. Distribution of the gross vehicle weight between the axles: a) six-axle sets, b) five-axle sets

Spearman correlation coefficients between axle loads and gross wehicle weight

As described in the methodology, the gross vehicle weight of the transport unit from the stationary scale was used for the analyses of the contribution of individual axles to GVW, rather than the sum from all axles (due to the assumed 5% error). The distribution of GVW mass varies between axles as well as between types of transport units. Therefore, a correlation analysis was performed between axle loads and GVW of the unit. In the six-axle sets, statistically significant correlations were obtained for all axles, where the largest coefficient of 0.5435 is for the sixth axle in the TT set, and the other axles of this set have larger values than in the TS (Table 6). In the five-axle sets, the correlation coefficients are much higher at 0.4152 (axle 3 in the TT set) to 0.8031 (axle 4 in the TD set).

Table 6. Spearman correlation coefficients between axle loads and GVW

Axle	Six-axle sets		Five-axle sets			
	TS	TT	TS	TT	TD	TP
Axle 1	0.1864	0.2608	0.5316	0.5330	-	0.6123
Axle 2	0.3275	0.3835	0.2995	0.4152	0.6734	-
Axle 3	0.3826	0.4532	0.6817	0.5725	0.6857	-
Axle 4	0.3698	0.3956	0.7763	0.6316	0.8031	0.6413
Axle 5	0.4457	0.4309	0.7420	0.5886	0.7718	-
Axle 6	0.3841	0.5435				

- no statistically significant correlation

a)

b)

c)

d)

Fig. 6. Transport set truck and semi-trailer with different wood assortments: a) five-axle (3+2) with Ls; b) six-axle with Sw4.4; c) five-axle with Sw8.8; d) six-axle with Sw4.0

a)

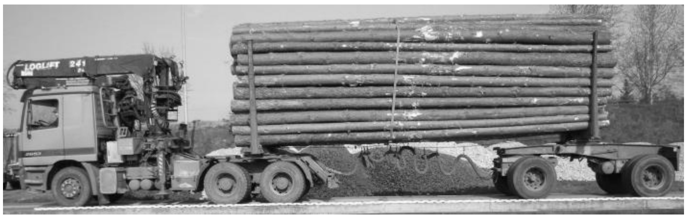
b)

c)

d)

Fig. 7. Transport set truck and trailer with different wood assortments: a) six-axle with Ms; b) six-axle with Sw5,0; c) five-axle with Sw4,0; d) six-axle with Sw3.7

a)



b)

Fig. 8. Transport set five-axle, truck and dolly with different wood assortments: a) Sw 8.8; b) Ls

Discussion

Studies conducted over several years have collected a large empirical material (904 deliveries) for different combinations of transport units (6 combinations) with different wood assortments and GVW. At the same time this is one of the reasons for the large range of results in the individual axle loads of the transport set (Table 1). Large-scale studies on axle loads of wood transport units are not often presented in the literature and use generic data from preselection measurements [Abeney 2003, Owusu-Ababio and Schmitt 2014], with concomitant shortcomings of this system [NIK 2014, Brunos et al. 2021; Brunos and Rys 2017] or from forest contractors [Hamsley et al. 2006]. Measurements of axle loads for round wood transportation on platform scales are mainly concerned with studies of specific units to determine the effect of axle loads on forest road surfaces based on calculations of axle load equivalency factors and include a small study group of sets from 5 to 65 [Martin et al. 1999; Ababio and Schmitt 2016; Šušnjar et al. 2011a]. Baumgras [1976] performed axle load analyses in West Virginia for 14 transport trucks (three axles) based on 543 measurements.

Analyzing the transport units of almost ten years, we observed a change in the types of sets, where six-axle sets predominate and there are no transports by truck and dolly) and truck and lightweight semi-trailer sets, which is a result of the change in the assortments of transported wood and the legislation and its modifications [Regulation...2002; Regulation...2018; Trzciński and Tymendorf 2017]. Changes in transport units are also due to legal changes defining GVW and transport companies adapting to customer demands and improving transport efficiency [McKinnon 2005; Pålsson et al. 2017; Väätäinen et al. 2020; Liimatainen et al. 2020; Brown 2021].

Turning to the discussion of the results of loads on particular axles and the factors that determine them, it is clear that in Poland it is the regulations that introduce the determination of wood mass on the basis of wood density conversion factors [Act...2012; Regulation 2012]. Using the conversion factors e.g. for pine 740 kg/m^3 the forester supplies so much wood that after taking into account the weight of empty transport unit does not exceed GVW. However, in our study we obtain average weights of transport sets at the level of 46-51t, which means exceeding the GVW=40t (Table 4). The problem of overloading of transport units is not a new issue and has been widely described in the literature, as mentioned in the introduction. The problem of using conversion factors for wood transport has been addressed in two reports of the Supreme Audit Office [NIK 2014 and 2018] and many information of the Road Transport Inspection [web information].

With such a high real GVW, overloading of any of the axles beyond the permissible values can also be expected, and this is what we found in our study. However, axle overloading is not only necessarily due to GVW, as confirmed by the study of Baugras [1976], where GVW overloading was found for only 1.46% of transports and truck tandem axle overloading in 58.1%, a similar situation is presented by Owusu-Ababio and Schmitt [2015].

Similar results of axle loads ranging from 8.3 to 13.3t for a seven-axle Volvo combination with a four-axle trailer were presented by Mackenzie [2008]. In other studies (after converting from pounds Ibs to tons) with GVW values of 35-45t, axle loads were obtained with very different values from 3.5t to 11.5t, which is also confirmed by our study (Table 5). This is largely influenced by the arrangement of the load, as exemplified by Fig. 6-8, and the length (assortment) of the transported wood, as confirmed by statistical analyses (Fig. 1b, 2, 3b and 4).

The weight distribution of the GVW unit on the truck and trailer/semi-trailer and dolly (TT, TS, TD) on average are close to 58-60% and about 40%, respectively, which is due to the drivers' actions in arranging the load to ensure the stability and traction of the truck (drive axle). The obtained values of GVW distribution on truck and trailer/semi-trailer are consistent with other works [Šušnjar et al. 2011b; Owusu-Ababio and Schmitt 2015; Šušnjar et al. 2016]. The percentage share of individual axles in GVW also depends on the wood assortment and its arrangement (Figs. 6-8), where statistically significant similarities can already be found between some transport sets (TT and TS , TD and TP and TS and TD), which may be the result of transporting similar wood assortments (Figs. 2 and 4).

The obtained results of the study, especially for the second axle of the truck in all units (9.15-12.43t), as well as for other axles of the transport set, ranging from 7.29t to 18.85t in Q3 (75% of the results), indicate that the real impact of the transport unit on the forest road surface will be higher. With the current standards for forest road pavement design under 10t axles [Czerniak et al. 2013], it is reasonable to analyze the calculation of ESAL axle load equivalence factors

[AASHO 1993; Martin et al. 1999; Varin and Saarenketo 2014; Owusu-Ababio and Schmitt 2015] on the basis of the conducted studies and their results.

Conclusions

Studies conducted over several years have built a large empirical database for different combinations of transport units with different wood assortments and gross vehicle weight. At the same time this is one of the reasons for the large range of results in the individual axle loads of the transport set.

The study showed that the actual axle loads of round wood transport vehicles depend on the gross vehicle weight of the transport unit and the type of set.

The variety of loads of the transported wood assortments has contributed to changes in the transport units allowing their transport, which consequently leads to overloading of some axles of the set.

On average, the weight distribution of the GVW truck-and-trailer/semi-trailer and dolly combination are similar. It is a result of drivers' efforts in arranging the load (round wood) to ensure the stability and traction of the vehicle, especially the drive axle.

References

AASHO [1993]: Guide for Design of Pavement structures. Highway research board, American Association of State Highways and Transportation Officials, Washington DC. [accessed 4.01.2022] https://habib00ugm.files.wordpress.com/2010/05/aashto1993.pdf

Abeney E.A. [2003]: Timber transport by road in Ghana. Ghana Journal Forestry [11]: 52-60. https://www.fornis.net/sites/default/files/documents/Timber_transport.pdf

Asmoarp, V., Enström, J., Bergqvist, M., von Hofsten, H., 2018: Improving Transport Efficiency – Final Report of the ETT 2014–2016 Project. Skogforsk, arbetsrapport 962–2018, 65 p. https://www.skogforsk.se/contentassets/d036107f3f2c49ff8d1bfb8d9e122ba1/arbetsrapport-962-2018.pdf

Baumgras J.E. [1976]: Better load-weight distribution is needed for tandem-axle logging trucks. Res. Pap. NE-342. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 9p. ne_rp342.pdf (fs.fed.us)

Brown M. [2008]: The impact of tare weight on transportation efficiency in Australian forest operations. CRC for Forestry. Bulletin 3: 1–4.

Brown M.W. [2021: Evaluation of the Impact of Timber Truck Configuration and Tare Weight on Payload Efficiency: An Australian Case Study. Forests 12 [7]: 855 https://doi.org/10.3390/f12070855

Brunos P., Rys D. [2017]: The Effect of Flexible Pavement Mechanics on the Accuracy of Axle Load Sensors in Vehicle Weigh-in-Motion Systems. Sensors 17 [9]: 2053 https://doi.org/10.3390/s17092053

Burnos P., Gajda J., Sroka R., Wasilewska M., Dolega C. [2021]: High Accuracy Weigh-In-Motion Systems for Direct Enforcement. Sensors 21 [23]: 8046 https://doi.org/10.3390/s21238046

Czerniak A. (ed.), Grajewski S.M, Kamiński B., Miler A.T., Okoński B., Leciejewski P., Trzciński G., Madaj A., Bańkowski J., Wojtkowski K. [2013]: Wytyczne prowadzenia robót drogowych w lasach (Guidelines for carrying out road works in forests). OR-W LP w Bedoniu, Bedoń, Poland

Devlin G. J., McDonnell K. M. [2009]: Assessing real time GPS asset tracking for timber haulage. The open Transportation Journal [3]: 78-86

Directive (EU) 2015/719 of the European Parliament and of the Council of 29 April 2015 Amending Council Directive 96/53/EC Laying Down for Certain Road Vehicles Circulating within the Community the Maximum Authorised Dimensions in National and International Traffic and the Maximum Authorised Weights in International Traffic (Text with EEA Relevance). Available online: https://publications.europa.eu/en/publication-detail/-/publication/22b313fc-f3bc-11e4-a3bf-01aa75ed71a1/language-en (accessed 4.01.2022).

El Hachemi N., Gendreau M., Rousseau L.-M. [2013]: A heuristic to solve the synchronized log-truck scheduling problem. Computers & Operations Research 40 [3]: 666-673

Ghaffariyan M.R., Acuna M., Brown M. [2013]: Analysing the effect of five operational factors on forest residue supply chain costs: A case study in Western Australia. Biomass and Bioenergy [59]: 486–493

Greulich F. [2002]: Transportation networks in forest harvesting: early development of the theory: An. Proceedings of International Seminar on New Roles of Plantation Forestry Requiring Appropriate Tending and Harvesting Operations. September 29 - October 5, 2002, Tokyo, Japan: 57-65 http://faculty.washington.edu/greulich/Documents/IUFRO2002Paper.pdf

Hajek J.J. [1995]: General Axle Load Equivalency Factors. Transportation Research Record [1482]: 67-78

Hamsley A., Greene W.G., Siry J., Mendell B. [2007]: Improving timber trucking performance by reducing variability of log truck weights. Southern Journal of Applied Forestry [31]: 12–16

ITF [20190]: Permissible maximum weights of lorries in Europe. https://www.itf-oecd.org/sites/default/files/docs/weights-2019.pdf

Judycki J. [2011]: Equivalent axle load factors for design of rigid pavements derived from fatigue criteria. The Baltic Journal of Road and Bridge Engineering 6 [4]: 219–224

Koirala A., Kizhal A.R., Roth B.E. [2017]: Perceiving Major Problems in Forest Products Transportation by Trucks and Trailers: A Cross-sectional Survey. European Journal of Forest Engineering [3]: 23–34

Kozakiewicz P., Tymendorf Ł., Trzciński G. [2021]: Importance of the Moisture Content of Large-Sized Scots Pine (Pinus sylvestris L.) Roundwood in Its Road Transport. Forests 12 [7]: 1-14

Liimatainen H., Nykänen L. [2017]: Impacts of Increasing Maximum Truck Weight—Case Finland; Transport Research Centre Verne, Tampere University of Technology: Tampere, Finland, 2017; Available online: http://www.tut.fi/verne/aineisto/LiimatainenNyk%C3%A4nen.pdf (accessed 10.12. 2018)

Liimatainen H., Pöllänen M., Nykänen L. [2020]: Impacts of increasing maximum truck weight—case Finland. European Transport Research Review [12] 14 https://doi.org/10.1186/s12544-020-00403-z

Lukason O., Ukrainski K., Varblane U. [2011]: Economic benefit of maximum truck weight regulation change for Estonian forest sector. Discussions on Estonian Economic Policy [2]: 87–100

Martin A.M., Owende P.M.O., O'Mahony M.J., Ward S.M. [1999]: Estimation of the Serviceability of Forest Access Roads. International Journal of Forest Engineering 10 [2]: 55-61

McDonald T.P., Haridass K., Valenzuela J. [2010]: Mileage savings from optimization of coordinated trucking: An Proceedings of 2010 COFE: 33rd Annual Meeting of the Council on Forest Engineering, eds Mitchell D., Gallagher T., June 6-9, 2010, Auburn, AL. [CD-ROM]: 1-11

Mcdonnell K.M., Devlin G.J., Lyons J., Russell F., Mortimer D. [2008]: Assessment of GPS tracking devices and associated software suitable for real time monitoring of timber haulage trucks: An COFORD Annual Report 2008, Director E. Hendrick. COFORD, Dublin, Ireland. (accessed 5. 07. 2021) http://www.coford.ie/media/coford/content/researchprogramme/thematicareaharvestingandproducts/08gpstrack.pdf

McKinnon A.C. [2005]: The Economic and Environmental Benefits of Increasing Maximum Truck Weight: The British Experience, Transportation Research Part D: Transport and Environment 10 [1]: 77-95 https://doi.org/10.1016/j.trd.2004.09.0066

NIK [2014]: Wykonywanie wybranych zadań przez Inspekcję Transportu Drogowego z uwzględnieniem funkcjonowania Centralnej Ewidencji Naruszeń (Performing selected tasks by the Road Transport Inspection, taking into account the functioning of the Central Register of Violations). KAP-4101-003-00/2014. Najwyższa Izba Kontroli. Warsaw, Poland, https://www.nik.gov.pl/kontrole/wyniki-kontroli-nik/pobierz,kap~p_14_006_201407010932241404207144~01,typ,k.pdf

NIK [2018]: wykonywanie zadań przez zarządców dróg wojewódzkich w zakresie utrzymania, remontów. (Performance of tasks by regional road managers in the field of road maintenance, repair and protection i ochrony dróg). KIN.430.002.2018. id,17534,vp,20106.pdf (nik.gov.pl)

Owusu-Ababio S., Schmitt R.[2014]: Evaluation of Impacts of Allowing Heavier Log Loads in Northern Wisconsin During Spring Thaw. Wiscontin DOT. Putting Reserch To Work. https://wisconsindot.gov/documents2/research/WisDOT-Policy-Research-0092-11-16-final-report.pdf

Owusu-Ababio S., Schmitt R. [2015]: Analysis of data on heavier truck weights. Case study of logging trucks. Transportation Research Record, Journal of the Transportation Research Board 2478 [2]: 82-92

Palander T., Haavikko H., Kortelainen E., Kärhä K., Borz S.A. [2020]: Improving Environmental and Energy Efficiency in Wood Transportation for a Carbon-Neutral Forest Industry. Forests 11 [11]: 1194 https://doi.org/10.3390/f11111194

Pålsson H., Hiselius L.W., Wandel S., Khan J., Adell E. [2017]: Longer and heavier road freight vehicles in Sweden. International Journal of Physical Distribution & Logistics Management [47]: 603–622 https://doi.org/10.1108/IJPDLM-02-2017-0118

Regulation [2002]: Rozporządzenie Ministra Infrastruktury z dnia 31 grudnia 2002 r. w sprawie warunków technicznych pojazdów oraz zakresu ich niezbędnego wyposażenia.

Dz.U. 2003 nr 32, poz.262. (Regulation of the Minister of Infrastructure of 31 December 2002 on the Technical Conditions of Vehicles and Their Necessary Equipment).

Regulacion [2012]: Rozporządzenie Ministra Środowiska oraz Ministra Gospodarki z dnia 2 maja 2012 r. w sprawie określenia gęstości drewna. Dz.U. 2012 poz.536. (Regulation of the Minister of the Environment and the Minister of Economy of 2 May 2012 on determining the density of wood.)

Regulation [2018]: Rozporządzenie Ministra Infrastruktury z dnia 25 stycznia 2018 r. w sprawie sposobu przewozu ładunku. Dz.U. 2018 poz.361. Regulation of the Minister of Infrastructure of 25 January 2018 on the method of cargo transportation.

Shaffer R.M., Stuart W.B. [1998]: A checklist for efficient log trucking. Virginia Cooperative Extension publication. 420–094, http://pubs.ext.vt.edu/420-094 (Accessed 10.12. 2008).

Shaffer R.M.; Stuart, W.B. [2005]: A checklist for efficient log trucking. Va. Coop. Ext. 2005, 420-094, 1–5. Available online: http://hdl.handle.net/10919/54904 (accessed 15.09. 2020).

Sosa A., Klvac R., Coates E., Kent T., Devlin G. [2015]: Improving Log Loading Efficiency for Improved Sustainable Transport within the Irish Forest and Biomass Sectors. Sustainability [7]: 3017-3030

Šušnjar M., Horvat D., Zorić M., Pandur Z., Vusić D., Tomašić Ž. [2011a]: Comparison of Real Axle Loads and Wheel Pressure of Truck Units for Wood Transportation with Legal Restrictions. Pushing the boundaries with research and innovation in forest engineering. FORMEC 2011, October 9-13 2011, Graz, Austria, Microsoft Word - formec2011_B5_3_Šušnjar_Horvat_Zoric_Pandur_Vusic_ Tomašic

Šušnjar M., Horvat D., Pandur Z., Zorić M.[2011b]: Određivanje osovinskih opterećenja kamionskoga i tegljačkoga skupa za prijevoz drva. (Axle Load Determination of Truck with Trailer and Truck with Semitrailer for Wood Transportation). Croatian Journal of Forest Engineering 32 [1]: 379-388

Šušnjar M., Pandur Z., Bačić M., Zorić M.[2016]: Raspodjela mase tovara i osovinskoga opterećenja šumskih kamionskih skupova pri prijevozu jelova celuloznoga drva. (Distribution of Load Masses and Axle Loads on Forest Truck Units during Transport of Fir Pulpwood). Nova Mehanizacija Sumarstva [37]: 47-58

Trzciński G., Tymendorf Ł. [2017]: Dostawy drewna po wprowadzeniu normatywnych przeliczników gęstości drewna do określenia masy ładunku (Deliveries of wood after the normative calculators wood density to determine the weight of the load). Sylwan 161 [6]: 451-459

Trzciński G., Tymendorf Ł. [2021]: Transport Work for the Supply of Pine Sawlogs to the Sawmill, Forests 11 [12]: 1-12

Trzciński G., Moskalik T., Wojtan R., Tymendorf Ł. [2017]: Zmienność ładunków i masy całkowitej zestawów wywozowych przy transporcie drewna. (Variability of loads and gross vehicle weights in timber transportation). Sylwan 161 [12]: 1026-1034

Trzciński G., Moskalik T., Wojtan R. [2018]: Total weight and axle loads of truck units in the transport of timber depending on the timber cargo. Forests 9 [4]: 1-12

Tymendorf Ł., Trzciński G. [2020]: Multi-Factorial Load Analysis of Pine Sawlogs in Transport to Sawmill. Forests 11 [4]: 366

Act… [2012]: Ustawa z dnia 20 czerwca 1997 r. Prawo o ruchu drogowym. Dz.U 2021 poz. 450. (Act of June 20, 1997, Road Traffic Law). (Act of Law)

Act… [2016]: Ustawa z dnia 21 marca 1985 r. O drogach publicznych. Dz.U. z 2021 poz.1376. (Act of March 21, 1985 on public roads). (Act of Law).

Väätäinen K., Laitila J., Anttila P., Kilpeläinen A., Asikainen A. [2020]: The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators—

Discrete event simulation case study in Central Finland. International Journal of Forest Engineering. [31]: 156–170 https://doi.org/10.1080/14942119.2020.1757324.

Varin P., Saarenketo T. [2014]: Effect of axle and tyre configurations on pavement durability – a prestudy. ROADEX 2014, https://www.roadex.org/wp-content/uploads/2014/01/ROADEX_Axle_Tyre_Prestudy_15102014-Final.pdf

Zarządzenie nr 51 Dyrektora Generalnego Lasów Państwowych z dnia 30.09.2019 r. (Regulation No. 51 of the General Director of the State Forests of 30.09.2019; General Directorate of the State Forests: Warsaw, Poland, 2019). Available online: http://drewno.zilp.lasy.gov.pl/drewno/Normy/1._podzia_terminologia_i_symbole_-_ujednolicono_wg_zarz_54-2020.pdf (accessed 20.10.2020)

Özturk T.,Şentürk N. [2009]: Analisis of Pavement Construction on a Sample Forest Road Section in Sariyer Region. İstanbul Üniversitesi Orman Fakültesi Dergisi. Seri A 59 [1]: 55-70

List of standards

PN-93/D-02002. Round Wood. In Classification, Terminology and Symbols. Polish Standardization Committee: Warsaw, Poland

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