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Railway Vehicle Energy Efficiency as a Key Factor in Creating Sustainable Transportation Systems

Małgorzata Ćwil [1], Witold Bartnik [2] and Sebastian Jarzębowski [3,*]

[1] Department of Quantitative Methods and Information Technology, Kozminski University, 03-301 Warsaw, Poland; mcwil@kozminski.edu.pl
[2] Faculty of Transport, Warsaw University of Technology, 00-662 Warsaw, Poland; witold.bartnik.dokt@pw.edu.pl
[3] Logistics & SCM Center, Kozminski University, 03-301 Warsaw, Poland
* Correspondence: sjarzebowski@kozminski.edu.pl

Abstract: Railway transit forms the backbone of sustainable transportation systems, which are necessary to limit the effects of global warming. In this paper, the authors seek to determine whether there is a statistically significant difference in energy consumption between distinct railway vehicle types. Firstly, the energy consumption measurement methods in the railway transportation sector are described and compared to each other in respect to precision and cost. Secondly, the use of energy consumption as a criterion in rolling stock tenders with the associated norm is analysed, particularly with regard to the life-cycle cost of railway vehicles. In the next part real life data on energy consumption of six distinct passenger electrical railway vehicle types is presented and analysed in order to compare the efficiency of different types of rolling stock. The differences in energy efficiency between rolling stock types may be used to improve the procurement process ensuring train operating companies obtain less energy-consuming vehicles.

Keywords: railway; energy efficiency; energy consumption

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1. Introduction

Transportation is a key element of the worldwide economic system, and its importance has particularly increased due to the rise of globalization and the transborder supply chains that have developed since 1990 [1]. It is, however, the only major sector of the EU economy whose CO_2 emissions have not been dropping in a sufficient manner. As shown in Figure 1, European transportation emissions have only started dropping in 2007 and still remain above their 1990 level [2]. This is a major challenge for global stakeholders as they strive to achieve the goals set in the Paris Agreement [3] in order to limit global warming to 1.5 °C. This requires significant emission reductions and transportation's comparable emissivity growth means this sector has to cut its environmental footprint faster and harder than the rest.

One of the major tools needed to achieve the aforementioned emission reduction is railway transportation. This importance stems from its numerous environmental advantages. Firstly, railway transportation boasts superior energy efficiency due to the low friction coefficient for steel wheels on steel rails [4,5]. Secondly, the widespread use of electrical engines and electrical traction for rail vehicles enables it to provide transportation with no emissions on-site, while the rise of green energy initiatives and the reduction of emissions in electricity production mean that a truly zero-emission railway is possible and has already been implemented, for example in the Netherlands [6]. Thirdly, railways are extremely efficient in terms of space required to provide transportation, which is the reason metros and urban rail systems form a critical component of sustainable cities [7]. Undoubtedly, railway transportation has numerous environmental advantages over its competitors and studying the differences in energy efficiency between various rolling stock types is a main aim of the research described in this paper.

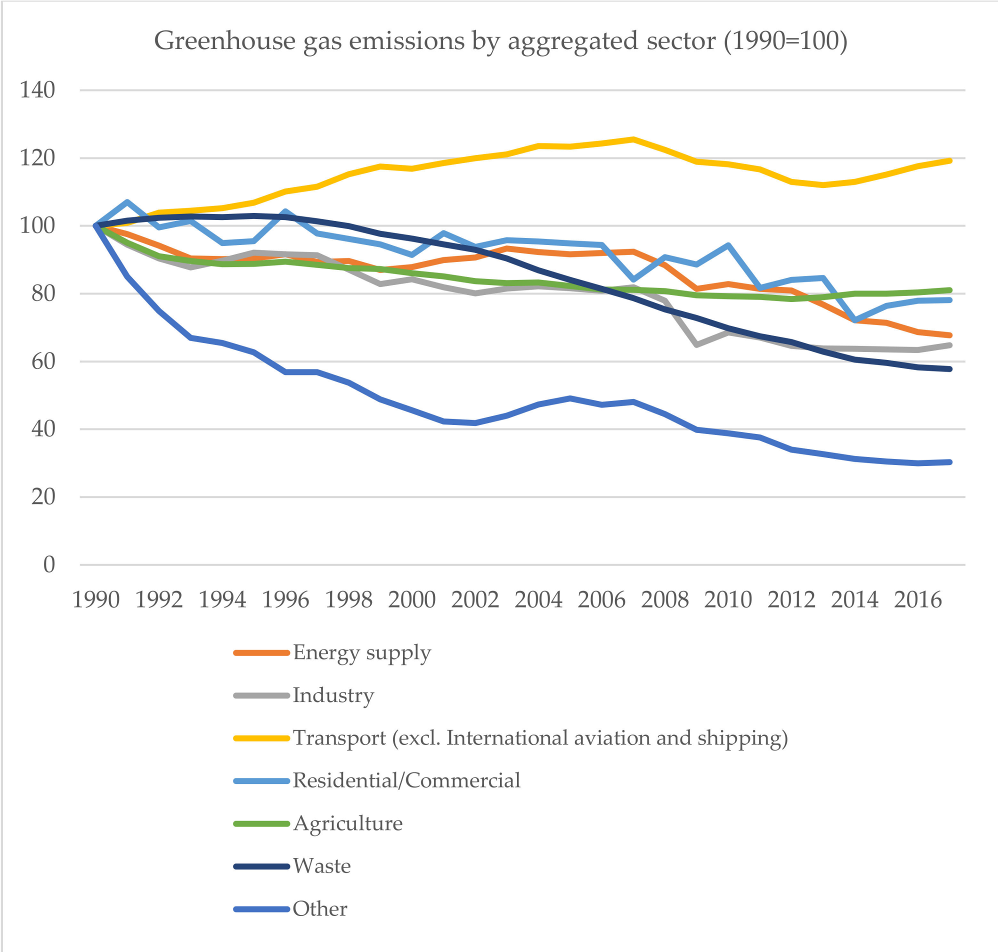

Figure 1. CO_2 emissions in European Union [3].

As the worldwide urban population is forecast to keep rising [8], the task of providing billions of city-dwellers with sustainable and affordable transport will have to be performed relying mostly on rail-based public transportation. Identifying the needs of customers enables train operators to offer the service that they need and require, in accordance with the value creation theory [9]. Furthermore, it has been shown that high-speed rail can compete with air travel on short corridors up to 1000 km [10]. This is made possible by the location advantage held by railway terminals over airports. Even though the flight time is shorter due to the significantly higher speed, the additional time needed by travellers to get to the outbound airport and then to move from the inbound terminal to the city centre causes these time savings to shrink. Furthermore, the complicated and often crowded security control procedure and waiting for luggage at the destination leads to even more time being lost as compared to departing from station 5 minutes after arrival and then coming immediately into the city centre with baggage on hand. This competition depends naturally on the location of the airport, as some terminals lie so close to the city centre as to render the train advantage irrelevant (i.e., New York La Guardia, Warsaw Chopin Airport). As short-haul flights emit more greenhouse gases, replacing them with railways powered by green energy offers a huge boost to the climate action. This process has already begun in France, where the terms of the government's pandemic-related help for Air France, a major airline, stipulate that the operator will need to stop competing with high-speed trains on connections between major French cities [11].

Environmental management system should provide an initial point for defining the management of environmental issues in a supply chain management context. Environmental management should encompass all efforts to minimize the negative environmental impact of the products throughout their life cycle [12]. These efforts should then focus on the procurement and production process, productive lifetime of the product and finally its disposal. Several studies have analysed the emission intensity of railways, particularly in order to compare it to competing modes. It is important to note that emission estimates for railways may vary significantly depending on the assessment method [13]. This stems from important approach differences between the three major emission calculation methods, namely direct emission, well-to-wheel (WTW) and life-cycle assessment (LCA). The WTW method in particular is important, as it takes into account the emissions generated during energy production, which can be problematic even for electric railways in countries or regions where energy generation is based mainly on coal or gas. Meanwhile, the LCA method emphasizes the emissions related to production and disposal of the vehicle after its productive lifetime is over.

2. Materials and Methods

2.1. Electrical Energy Measurement in Railway Vehicles

Improving railway transportation energy efficiency requires that efficiency be measured first. This task is quite straightforward for diesel-fuelled vehicles, as they require regular refuelling, but electrical vehicles draw power from the catenary and unless measuring devices are mounted onboard the only information available is via substation measurement. That can still provide valuable information and general consumption coefficients for the whole network can be calculated. This used to be the main method of energy settlement in European railway undertakings [14]. Each train would have its consumption coefficient calculated based on its mass, composition, stopping pattern and other factors [15]. Then the total energy consumption for a given period would be divided between all the trains running in that period according to their coefficients [16]. Although this method provides useful results, it is worth noting that in a system where energy is settled via coefficients, no incentive exists for more efficient operations. If any operator or a single train driver tries to run trains in a more efficient manner (i.e., uses eco-driving), the total gain from those efforts is spread evenly among all trains thus reducing the incentive for such environment-friendly actions.

This underlying weakness of the settlement system was observed by the European Union Agency for Railways (ERA) and has led it to ask the European Committee for Electrotechnical Standardization (CENELEC) to create a standard for an onboard energy measuring system (EMS) [17]. This standard was established as the norm EN-50463: "Railway applications. Energy measurement on board trains. General" [18].

To pay only for energy that was actually consumed by their trains, operators have started to install energy meters on their vehicles [19,20]. These devices also allow them to monitor operating efficiency of vehicle types, drivers and routes enabling better decision-making. At the same time, energy meters allow the energy provider to analyse the quality of the power supply and can even be used to detect abnormalities related to catenary or substation problems. These advantages of a fully measured system have been noticed by regulators. The EU in particular has, via its Technical Specifications for Interoperability Energy documents, established a general requirement for all operators of electrical trains to mount energy meters onboard, while obliging infrastructure operators and energy providers to construct data collection and billing systems. All such devices and systems must conform to the aforementioned EN 50463 norm. Railway undertakings in Europe have declared that they will install Energy Measurement Systems (EMS) on all traction units where it is technically and economically feasible, which should result in the metering of 60% of all traction vehicles by 2025 and 90% by 2030 [21]. Metering therefore has numerous benefits for both the operator and the energy provider, but these come at a cost, as these devices require investment and regular maintenance in order to ensure their continued precision. For example, in Poland the cost of procurement and installation for one meter was estimated to be between PLN 11–30 thousand (ca. EUR 2500–6700) [22], while at the same time metrological legislation required the recertification of those devices every three years forcing operators to implement procedures related to that process and to keep additional meters in reserve.

Modern rail vehicles often include advanced TCS (Train Control System) which collect and analyse data from numerous sensors mounted onboard. As some of these sensors are installed in the engines and the inverter (modern vehicles run almost exclusively using AC engines, while legacy networks often use DC power supply), it is possible to determine the energy consumption through the power input measurement. That method is only an estimate as the sensors providing data for it do not need to conform to energy metering specifications. It can; however, be used as a tool for trip efficiency evaluation.

2.2. Factors Affecting Energy Consumption

Energy consumption of running trains is influenced by several factors [23]. Firstly, there is a division between energy used to propel the train and the energy needed to run its systems, heating, ventilation, air-conditioning (HVAC) and lights. The running energy for passenger trains depends strongly on the type of service being operated due to their different stopping patterns. As the data from the Spanish operator RENFE shows [24], despite the higher maximal speed of long distance and high-speed trains, their energy consumption per passenger-km is significantly lower than for commuter and regional trains. This stems from the fact that accelerating the train after it has been stopped completely is highly energy consuming. For trains running similar services, the maximal speed attained also affects the energy consumption significantly. As the kinetic energy increases squarely with speed, that effect is particularly strong for higher speeds, where the increase from i.e., 130 km/h to 140 km/h for a commuter train does not provide significant time savings while leading to higher energy consumption. The driving technique employed by the vehicle operator is also a significant factor influencing the total energy intake of the train [25], which has led some operators to implement eco-driving as a method of increasing their operational efficiency. These approaches are often based on Driver Advisory Systems (DAS) which supply drivers with dynamic speed recommendations [26]. Another important factor affecting the level of energy consumption in passenger trains is the weather. Low temperatures require the train to be heated, which in cold winters may increase the energy use by over 30%. Conversely, due to the fact that an increasing number of trainsets is equipped with air conditioning, hot weather leads to increased energy consumption for cooling.

2.3. Energy Consumption as a Tender Criterion

The procurement function has become very important for the organizations to influence their response to the natural environment issues. Procurement plays strategic role in an organization and is integrally related with the formation of trading partnerships [27]. The environmental criteria in purchasing constitute a very recent research topic, the study of these issues is not sufficient. There are various literature references related to environmental aspects in procurement [28–32]. The common issue is the integration of environmental aspects and concerns into sourcing and supply chain management [33,34] in order to improve the environmental impact of the supply chain while maintaining results in economic performance [35–41]. There are also literature sources focusing on governmental requirements and legal regulations in relation to environmental protection and CSR [37,42–46].

Railway vehicle procurement used to be based entirely on price. While this approach has its merits and was the only choice available when there was a lack of sufficient data to establish the value of other vehicle life cost components, it has been superseded by a LCC (life-cycle cost) method. According to this methodology, when evaluating the cost of owning an object, its whole life cycle is taken into account, including the initial investment, maintenance, energy as well as its disposal [47]. In a railway vehicle, this last part is not necessarily significant and it has therefore become standard to define a TCO (total cost of ownership) of a train as a sum of the initial price, maintenance and energy costs. There are varying estimates of the weight of these components in the total cost of ownership, but in general public information in that area is limited. This is mostly due to the confidential character of such data, as disclosing it would negatively affect an operator's competitive position. The estimates available to the authors have been shown in Table 1.

Table 1. Lifecycle components' value.

Source	Procurement	Maintenance	Energy
Arup, 2011	31%	44%	25%
Siemens, 2016	34%	29%	37%

Source: [48,49].

These percentages also vary between different types of service patterns operated by trains. The more frequently the train stops, the higher its specific energy consumption which will also affect its total life cycle cost. On the other hand, high-speed trains, whose stopping pattern is very infrequent, incur a high procurement cost due to the technological and safety requirements of regulators for this kind of vehicles.

The rising awareness of maintenance and energy costs has led operators to start using LCC analysis in their tendering process. The first such tender was floated in 1986 by the Swedish State Railways [50]. The use of energy coefficients in the tendering process is a more recent development and there have been varying approaches to this subject. An often-used method is to specify a route, usually operated by the tendering entity and to require producers to declare the amount of energy needed to run that route. This was the approach used by the Masovian Railways (Koleje Mazowieckie, a large regional operator in Poland) in their huge, 71 electrical multiple unit (EMU) tender in 2017 [51]. The bidders had to specify the total consumption of energy of their trains on the route (both ways) from Warsaw to Minsk Mazowiecki in the least favourable conditions possible out of the predefined set where the required temperature was between −15 and +30 °C A similar approach has been used by Łódź Metropolitan Railway (ŁKA-Łódzka Kolej Aglomeracyjna, a small urban rail operator in Łódź), although in that tender the energy consumption was multiplied by the declared vehicle weight in the final evaluation score. In both cases this method of establishing energy efficiency has led to protests by the losing bidders and in the case of the ŁKA tender the winning bidder's calculation was overturned and the final result changed. The main problem with using this criterion is its declarative character—the vehicle's true efficiency can only be measured after delivery, when it is already too late to affect the bidding process. The percentages used to evaluate rolling stock tenders in Poland in the last few years are shown in Table 2 on the basis of the tender documents from those procurement processes. As indicated in the table, energy costs were present in the evaluation criteria for the majority of those tenders.

Table 2. Rolling stock evaluation criteria in Polish tenders.

Train Type	Procurer	Purchase Costs	Maintenance Costs	Energy Costs	Other Criteria
ED160	PKP Intercity S.A.	40%	30%	30%	0%
ED161	PKP Intercity S.A.	40%	30%	30%	0%
Flirt 3	ŁKA	40%	30%	25%	5%
36 WE	ŁKA	40%	30%	20%	10%
Flirt 3	KM	20%	25%	13%	39%
ED162	PKP Intercity S.A.	58%	22%	0%	20%
ED250	PKP Intercity S.A.	60%	40%	0%	0%

Source: Official tender documents.

A special norm, EN 50591, was developed in order to support railway undertakings in efficient rolling stock procurement [52]. In this document, a method for calculating the energy efficiency of railway vehicles is proposed taking into account factors such as train load, track speed profile, line topography and temperature. The norm divides railway services into six distinct categories, five for passenger traffic: metro, suburban, regional, intercity, high speed and one for mainline freight.

2.4. Energy Efficiency Improvement

To achieve sustainability of railway transportation, two distinct objectives have to be met. Firstly, the energy consumption has to be reduced to make trains cheaper and more competitive compared to their unecological alternatives. Secondly, their energy supply needs to become green as well.

The authors believe that the search for potential improvement of efficiency is not a task only for single enterprises but also for entire supply chains [53]. The subject of increasing the energy efficiency of railway transportation has been analysed extensively in literature. The seminal work by Gonzales-Gil et al. [54], which focuses on DC-powered urban rail systems, provides great insight into this topic. The potential improvements are divided into five main categories: regenerative braking, energy efficient driving, traction efficiency, comfort functions and measurement and management. All of these areas have been the subject of intense research, and a detailed description falls outside the scope of this paper, but it is worth noting that regenerative braking and energy efficient driving concepts contain the bulk of the savings potential which has led to numerous mathematical publications describing the optimal driving curve for trains in differing conditions, schedules and service types [55]. Reducing the braking losses through smooth driving is also mentioned as a significant source of energy saving potential in other sources [56]. These losses can also be reduced by using energy storage with two main approaches used in the industry: trackside- and vehicle-mounted devices [57]. Modernising old and procuring new train sets also provides a huge sustainability boost, particularly because railway vehicles may serve for over 50 years, compared to only 10–12 years for buses. Another important method of improving the railway energy efficiency is the prevention of route conflicts which in cases of heavy trains and high operational speeds can lead to energy losses as high as 100 MJ [56].

The topic of green power supply for railways has become very popular in recent years. Although this subject may be outside of control of the railway operator, it is worth noting that the source of the energy used to power trains is critical to their sustainability. For example, because the majority of electrical energy (74% in 2021) produced in Poland comes from burning coal, its mostly electrified and extensive railway network has a large carbon footprint [58]. The national energy provider (PKP Energetyka) has therefore declared that by 2030 all of the energy consumed by the Polish railways will be renewable. Achieving goals similar to that will be of critical importance in order to achieve emission targets prescribed by the Paris Agreement. Measuring and assessing the energy consumption of existing rolling stock is therefore an important part in the process of increasing the efficiency of railways.

2.5. Research Methods

To research the differences in energy consumption between train types, the following hypothesis is stated:

Hypothesis 1 (H1). *The energy consumption differs between distinct train types.*

Data from 6 distinct types of electric, passenger railway vehicles was gathered and analysed. These data were collected from energy meters mounted on trains operated by a large operator in Eastern Europe. The accumulated data consists of over 1 million trips (N = 1,042,716) made between April 2016 and December 2020. Besides the energy consumption, the researchers additionally gathered the data concerning: train type (with its weight and number of cars), date of the measurement (which allows to include the temperature or compare the energy usage between different seasons). It is worth noting that the objective of this research was to determine whether any differences in specific energy consumption stemming from technical differences could be detected. For electrical multiple units these differences may be caused by different approaches to the vehicle construction, for example the number of powered and unpowered cars or the total number of axles. This means that for that comparison to be worthwhile, other factors affecting energy consumption needed to be similar for all train types analysed. Data from all vehicles were gathered in similar numbers across all seasons and temperatures typical for Central Europe which enabled the authors to disregard that factor although it might be interesting to model how the change in temperature affects each type's energy consumption separately. The same applies to the number of passengers, which could not be measured for the purposes of this research; however, the very large sample size and the equal use of analysed trainsets in different types of day allows the authors to assume that this factor was not relevant in the detected differences.

The six vehicle types included in the analysis varied by their length, mass, passenger capacity, and electrical engine type. The vehicles analysed had either a direct current (DC) or alternating current (AC) propulsion. DC engines are not installed on modern railway vehicles anymore, but before the invention of efficient inverters companies operating DC traction had to use matching engines on their vehicles. AC engines are now widespread due to their higher efficiency, particularly in the acceleration phase. Regenerated energy was not taken into account in these calculations due to the random character of the network receiving capability and the fact that DC-powered trains are not able to use regenerative braking. The stopping pattern was similar among all the services operated by those railway vehicles and the terrain was mostly flat, so it did not affect the energy consumption significantly. To obtain a fair comparison between those train types, their energy consumption per kilometre (Unit Energy Consumption) was divided by their net running mass in tonnes, so the final unit of measurement was watthour/tonnekilometer (Wh/tkm). This unit appropriately represents the amount of energy required to power different trainsets and allows for comparable analysis.

Each of the six researched train types was represented by a vast number of trips (Table 3). The lowest number of trips was reported by the train type no. 6 (n = 69,803, 6.7% of all the trips) and the highest by the train type no. 4 (n = 358,413, 34.4% of all the trips).

Table 3. Number of trips analysed for each of the included train types.

Train type	Frequency	Percent
1	81,158	7.8
2	145,607	14.0
3	272,127	26.1
4	358,413	34.4
5	115,608	11.1
6	69,803	6.7
Total	1,042,716	100.0

All data were analysed using SPSS v. 26 (Version 26.0. Armonk, NY: IBM Corp.). There were no missing data about energy consumption or the train type in the whole data set. To compare the energy usage between distinct train types, ANOVA analysis was performed. ANOVA provides a statistical test of whether two or more population means are equal, it this case the average energy consumption between train types was tested [59]. ANOVA analysis was used to verify the hypothesis that the energy consumption differs between distinct train types. If the results of the test indicate that there are significant differences in energy usage between distinct train types, the authors would suggest that the energy factor should be included as one of the tender criteria.

3. Results

The average energy consumption for researched train types ranged from 43.862 Wh/tkm to 59.995 Wh/tkm (Table 4). The values of the means and medians did not differ significantly. On the basis of skewness, the distributions of energy consumption for all of the train types were not highly asymmetrical. The values of standard deviation show that the variability of the scores was rather mild; however, on the boxplots a large number of outliers can be observed (Figure 2).

Table 4. Energy consumption descriptive statistics for each of the train types.

JZE_Wh/tkm		Train Type					
		1	2	3	4	5	6
N	Valid	81,158	145,607	272,127	358,413	115,608	69,803
	Missing	0	0	0	0	0	0
Mean (M)		51.7326	43.8621	50.3594	54.6107	57.9052	59.9948
Median		52.1570	43.1412	50.6346	55.1813	58.0802	60.0966
Std. Deviation (SD)		9.10781	10.21695	10.50929	9.08018	9.81526	7.98946
Skewness		−0.241	0.773	0.179	−0.192	−0.310	0.759
Minimum		0.27	0.06	0.07	0.02	0.18	0.53
Maximum		172.24	239.97	232.07	223.11	212.69	219.35

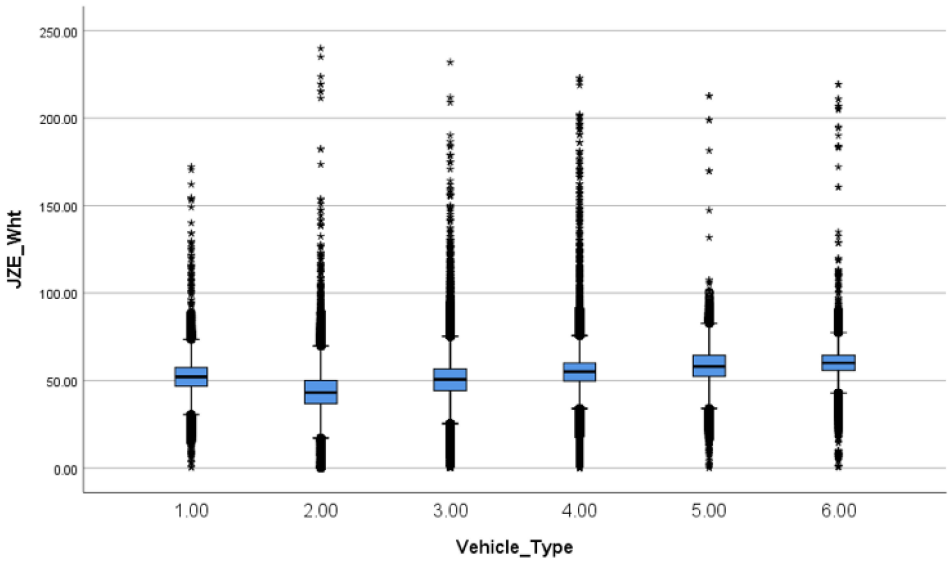

Figure 2. The comparison of energy consumption for each of the vehicle types. Stars denote atypical observations.

According to Figure 2, some differences in energy consumption per one tonnekilometer can be observed. The lowest energy consumption is observed in train type no. 2 (according to median and quartiles) and the highest in train type no. 6.

To verify the hypothesis that there is a statistically significant difference in the energy consumption between different train types, a one-way ANOVA for independent samples was performed with the robust test of equality of means (Table 5). The statistical tests were used in order to generalize the results for the whole population. It turned out that there are statistically significant differences in energy usage between different train types (F Welch (5; 310,150.05) = 45776.12; $p < 0.001$, $\eta^2 = 0.18$). The observed effect is strong [60].

Table 5. The results of ANOVA test.

ANOVA					
JZE_Wht					
	Sum of Squares	df	Mean Square	F	Sig. (p)
Between Groups	21,054,343.5	5	4,210,868.7	45,204.318	0.000
Within Groups	97,130,431.4	1,042,710	93.2		
Total	118,184,774.9	1,042,715			
Robust Tests of Equality of Means					
JZE_Wht					
	Statistic [a]	df1	df2	Sig.	
Welch	45,776.120	5	310,150.051	0.000	

[a] Asymptotically F distributed.

The following analysis was used to test in which pairs of trains the statistically significant differences in energy consumption can be observed. To verify this, the post hoc Games–Howell test was performed (Table 6). The Games–Howell test was chosen to compare all possible combinations of group differences because the assumption of homogeneity of variances was violated. The highest energy consumption per one tonne of weight was observed in the train type no. 6 (M = 59.995, SD = 7.989). The mean score for this train type is significantly higher than for the train type no. 5, which is the second in order (M = 57.905, SD = 9.815, $p < 0.001$, Cohen's d = 0.059, 95% CI_{diff} [1.971;2.209]). The third in order taking into consideration energy consumption per one tonne is train type no. 4 and the difference between this train type and no. 5 is statistically significant (M = 54.611, SD = 9.080, $p < 0.001$, Cohen's d = 0.087, 95% CI_{diff} [3.202;3.387]). Significantly lower energy consumption was observed in train type no. 1 (M = 51.733, SD = 9.108, $p < 0.001$, Cohen's d = 0.079, 95% CI_{diff} [2.777;2.979]). The next in order is train type no. 3 (M = 50.359, SD = 10.509, $p < 0.001$, Cohen's d = 0.035, 95% CI_{diff} [1.266;1.481]). The lowest energy consumption was observed in train type no. 2 (M = 43.862, SD = 10.217, $p < 0.001$, Cohen's d = 0.157, 95% CI_{diff} [6.402;6.593]) (Table 6).

Table 6. The results of Games–Howell test.

Multiple Comparisons						
Dependent Variable: JZE_Wht						
Games–Howell						
(I) Vehicle_Type	**(J) Vehicle_Type**	**Mean Difference (I-J)**	**Std. Error**	**Sig. (p)**	**95% Confidence Interval (CI)**	
					Lower Bound	**Upper Bound**
1	2	7.87055 *	0.04170	0.000	7.7517	7.9894
	3	1.37323 *	0.03779	0.000	1.2655	1.4809
	4	−2.87808 *	0.03539	0.000	−2.9789	−2.7772
	5	−6.17257 *	0.04307	0.000	−6.2953	−6.0498
	6	−8.26216 *	0.04401	0.000	−8.3876	−8.1368
2	1	−7.87055 *	0.04170	0.000	−7.9894	−7.7517
	3	−6.49731 *	0.03351	0.000	−6.5928	−6.4018
	4	−10.74863 *	0.03077	0.000	−10.8363	−10.6609
	5	−14.04311 *	0.03937	0.000	−14.1553	−13.9309
	6	−16.13271 *	0.04039	0.000	−16.2478	−16.0176
3	1	−1.37323 *	0.03779	0.000	−1.4809	−1.2655
	2	6.49731 *	0.03351	0.000	6.4018	6.5928
	4	−4.25131 *	0.02522	0.000	−4.3232	−4.1795
	5	−7.54580 *	0.03520	0.000	−7.6461	−7.4455
	6	−9.63540 *	0.03634	0.000	−9.7389	−9.5318

Table 6. *Cont.*

Multiple Comparisons						
Dependent Variable: JZE_Wht						
Games–Howell						
(I) Vehicle_Type	(J) Vehicle_Type	Mean Difference (I-J)	Std. Error	Sig. (*p*)	95% Confidence Interval (CI)	
					Lower Bound	Upper Bound
4	1	2.87808 *	0.03539	0.000	2.7772	2.9789
	2	10.74863 *	0.03077	0.000	10.6609	10.8363
	3	4.25131 *	0.02522	0.000	4.1795	4.3232
	5	−3.29449 *	0.03261	0.000	−3.3874	−3.2016
	6	−5.38408 *	0.03383	0.000	−5.4805	−5.2877
5	1	6.17257 *	0.04307	0.000	6.0498	6.2953
	2	14.04311 *	0.03937	0.000	13.9309	14.1553
	3	7.54580 *	0.03520	0.000	7.4455	7.6461
	4	3.29449 *	0.03261	0.000	3.2016	3.3874
	6	−2.08960 *	0.04181	0.000	− 2.2087	−1.9705
6	1	8.26216 *	0.04401	0.000	8.1368	8.3876
	2	16.13271 *	0.04039	0.000	16.0176	16.2478
	3	9.63540 *	0.03634	0.000	9.5318	9.7389
	4	5.38408 *	0.03383	0.000	5.2877	5.4805
	5	2.08960 *	0.04181	0.000	1.9705	2.2087

* The mean difference is significant at the 0.05 level.

When the energy consumption between the train types with the highest and the lowest score in the sample is compared, the difference is even more vivid. The train with the highest energy consumption (no. 6) uses 59.99 Wh/tkm on average while for the train with the lowest energy consumption (no. 2) the mean amounts to only 43.86 Wh/tkm ($p < 0.001$, Cohen's d = 1.887, 95% CI_{diff} [16.018;16.248]).

In summary, statistically significant differences in energy consumption can be observed between any of the six compared vehicle types. Between the trains with the highest disparity, the difference in energy consumption reached more than 20%. This knowledge can be beneficial when making decisions about railway vehicle procurement and use.

4. Discussion and Conclusions

The objective of this article was to establish whether there are significant differences in energy consumption between distinct train types. Firstly, the problems related to making railway transportation sustainable were presented. In particular, the lack of progress in reducing transportation sector emissions was pointed out. The challenges of energy measurement in electrical railway transportation were described, as well as the EU normative actions directed at metering all vehicles on European railways. The growing importance of energy consumption in railway operators' business planning due to the LCC approach was highlighted, with several examples of tenders shown, where the energy efficiency criterion was used in order to procure more economical trains. The lack of research analysing the energy consumption of trains based on real world data was established. Finally, real-life data on energy consumption from trains operated by a large regional passenger operator in central and eastern Europe were presented and analysed in order to discern the differences in energy efficiency between distinct types of electrical multiple units. These differences are statistically significant and point to large potential energy savings to be obtained through rolling stock modernisation and procurement. Among all the trains that have been included in the research, the differences in energy consumption reach more than 20%, which highlights the long-term advantage of procuring energy-efficient trains. It is also worth noting that the existing body of research in this field has either proposed theoretical models of energy consumption [61] or analysed the real energy consumption, but for high-speed electrical multiple units only [23], for which the factors affecting consumption are significantly different from those for regional trains. This research has therefore extended the existing knowledge in the field of railway energy consumption. It may, however, be worthwhile to continue this research with the explicit objectives of determining the factors causing these statistically significant differences as well as obtaining a verifiable mathematical model enabling the proper estimation of energy consumption of electrical multiple units. Such research should in particular look at the differences in construction mentioned in Section 2.5.

At this time, however, many tenders do not account for an energy consumption component in their structure (see Table 2) and as the aforementioned differences in energy efficiency show, this would be beneficial both for the railway operators and the environment. These steps are necessary to make railways more sustainable and cut their emissions, which will become critical when CO_2 emission permits become more expensive. The results shown in this paper can support railway operators in the preparation of tenders for the procurement of new trains as well as in analysing the potential benefits of modernising older rolling stock. The observed differences in energy consumption may serve as guidelines for correct criteria value assignment as well as for cost–benefit analysis in rolling stock decisions at the strategic level. At the same time, that knowledge may help policy makers to determine the role which the railway transportation has to play in the global drive towards sustainability and limiting the effects of global warming. The aforementioned results can also be used by academics studying the energy efficiency issues related to railway vehicles, both on the technical as well as economical side. All these efforts would be well supported by future research directed at establishing more insights about the railway vehicles' energy consumption and factors affecting it, as it will help operators plan their costs better.

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