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Energy Efficiency of High-Speed Railways n

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Abstract

The world is becoming more dependent on energy resources, which translates into political dependency on energy-exported states. This will significantly impact the economy, transport, and the environment around the world. Railway transport is becoming an essential mode of transportation because it can operate on an electrified network and has zero carbon emissions. High-Speed Railways (HSR) is an energy-intensive transport system, and it is important economically and environmentally to reduce the amount of used energy. This study examined high-speed rail from an energy efficiency point of view and found factors that can significantly reduce the energy consumption of high-speed rail. This research aims to answer the question that motivated this research: what fundamental factors affect the energy consumption of the selected HSR systems? It estimated the dynamic changes in the total energy consumption for seven HSR systems from 2010-2017 and benchmarked the most energy efficient HSR systems. The non-radial Data Envelopment Analyses methodology has been used to fulfil this research. To conduct complex statistical analyses, IBM SPSS has been applied. The main findings have shown that the decrease in vehicle mass, improved design of high-speed rolling stock and increased occupancy of trains will support the reduction of energy consumption by high-speed railways. The changes in energy consumption strongly correlate with the type of high-speed rolling stock and operational strategies. The expected outcomes of this research will contribute to developing and advancing more sustainable HSR systems. This research will support train operators in making decisions when acquiring new trains and assess the benefits of acceleration in modernising the current rolling stock.

Keywords

High-speed railway; rolling stock; energy; efficiency; sustainability

1. Introduction

The sustainable development of society can be affected by the scarcity of natural resources and the creation of pollution that limits the growth of economies. Transport accelerates economic growth, uses non-renewable natural resources, and produces pollution. In 2012 the share of CO_2 emissions produced by transport globally was 23.1%, but by 2015 the share of transport CO_2 emissions increased to 24.7% [1]. The most significant evolution in developing sustainable transport systems will be reducing energy consumption and improving energy efficiency. Improvement in energy efficiency will not only support decreasing production of CO_2 emissions but also reduce the cost of railway transportation and increase the competitiveness of railways towards other transportation modes [2]. The energy efficiency improvement of railway systems is an integrated approach involving different participants' cooperation. Development of High-Speed Railway (HSR) systems increases worldwide, with China as the leader in the construction of HSR. HSR gained a reputation as one of the safest, most effective, and most sustainable modes of transportation. HSR has been studied from different points of view: economic, environmental, social, and technical. This research looked at the energy efficiency of the selected HSRs as an essential factor in improving the sustainability of HSR systems. In previous studies, much attention was paid to the efficiency of rail vehicle equipment, optimization of the speed profile and traffic scheduling.

In the last years, energy cost has taken on increasing importance. Reducing the energy consumption by HSRs will not only reduce CO_2 emissions but also make railways more competitive with other modes of transportation. Wang Yan-Zhe et al., 2021 [3] developed a new lifecycle model of energy consumption and greenhouse gas emission on China’s HSR. The study found the essential factors that influence the lifecycle energy consumption of HSRs, such as the electricity generation mix and full load. Malgorzata Cwil et al., 2021 pointed out the lack of progress in reducing energy consumption and CO_2 emissions in the railway sector. They defined the statistically significant difference in energy consumption between six distinct passenger electrical railway vehicle types. They suggested that the large energy saving can be achieved through rolling stock modernisation and renewal. The reduction of energy consumption can be achieved by replacing the rolling stock with more energy efficiency and effectively organising onboard equipment. That was highlighted in the works of Luca Pugi et al. and Zhuang Xiao et al. [4, 5].

Decreasing energy consumption and increasing energy efficiency will support the improvement of railway systems' environmental, economic, and social sustainability. This study aims to evaluate the energy efficiency of selected HSRs and identify factors that affect such efficiency. The objectives of this research are to compare selected HSRs in energy efficiency, define the factors that affect efficiency scores and make suggestions for improving the sustainability of HSRs. The authors studied the HSR as a system and identified factors that affect the energy consumption of the HSR system. In previous studies, the most common approaches were solving dynamic problems, installing energy measurement systems, and developing methods for calculating an energy-efficient speed profile and applying life cycle analysis models. This study proposes a method to evaluate the energy efficiency of HSRs and detects the factors that reduce energy consumption. The research highlighted important facts about energy efficiency for HSRs at the operational stage and extended the existing knowledge in the field of energy consumption by HSRs.

To empirically evaluate the selected HSRs' efficiency, the Data Envelopment Analysis (DEA) has been used. It has identified high and low performers and found the best practices within the selected group. The combination of several methods and different approaches has been used to identify the significant factors that influence the efficiency of HSRS in terms of energy used to provide the achieved number of passengers and passenger-km. Aggregated statistics, including numerical and non-numerical data, are collected, summarised, and included in the research to obtain a better picture.

The DEA methodology estimates the dynamic changes in the total energy consumption for the selected HSRs from 2010-2017 and benchmarks the most energy efficient HSRs. It was found that to reduce the energy consumption by High-Speed Rolling Stock (HSRS), it needs to decrease vehicle mass, improve the design of HSRS and increase the occupancy of trains. The reduction in the axle load will reduce energy consumption, increase train speed, and minimise infrastructure maintenance.

The following section explores the factors affecting a train's energy consumption and efficiency. The methodology used to complete this research project is presented in section 3. Section 4 reports the rolling stock analysis for the selected HSR, and section 6 reports the main findings and results concerning the energy efficiency of the selected HSRs. The analysis and discussion of the main findings are shown in section 7, whilst section 8 reports the key conclusions and recommendations for future work.

2. Literature Review

Railway transport is becoming an essential mode of transportation. It is a safe, fast, and comfortable way to travel. HSR allows passengers to move over long distances in a shorter time. HSR can help reduce the pollution from transport and congestion on roads. However, with the increasing price of energy and new technologies entering the market to remain competitive, railways must be efficient and sustainable. Energy efficiency will be beneficial in terms of economic, environmental, and social sustainability.

Back in the 1990s the European Conference of Ministers of Transport emphasised that apart from the benefits that transport can bring, there are some negative effects brought by transport. The adverse effects include accidents, congestion, air and noise pollution, energy, land, and other natural resources consumption to produce vehicles and infrastructures [6]. The economy cannot grow sustainably if society continues to use natural resources and produce pollution simultaneously. Technology and the behaviour of people must be changed.

"Railway Handbook 2017 Energy Consumption and CO_2 Emissions" highlighted that passenger railway transport in 2015 accounted for 9% of global passenger-km and only for 1% of passenger final energy demand, from which electricity accounts for three quarters [1]. Railway transport is the most efficient mass transportation mode. The electrification of railways becomes crucially essential for future carbon-neutral transport.

HSR network is developing very rapidly, especially in recent years. In global railway passenger transportation, between 2010 and 2015, the share of HSR increased from 10% to 20% [1]. Concerning this, it is essential to develop energy efficient HSR systems to help tackle climate change.

Recently several types of research covered different aspects of the energy efficiency of railway transportation, from the efficiency of rail vehicle equipment and optimisation of the speed profile to traffic schedule has been published. However, in many cases, only the overall energy consumption used by railway operators is known. The railway operators do not consider their rolling stock's actual energy consumption during operation. Martínez Fernández, P. et al. [7] reviewed and analysed a relatively large number of papers related to railway energy consumption by railways. They mainly concentrate on analysing the modelling techniques and optimisation methods used to simulate train movements and energy consumption and achieve more efficient train traffic. The authors found that the most common methods used in analysed papers are Genetic Algorithms, Decision Theory and Maximum Principal Analysis.

The influence of different components of railway systems on energy consumption by trains has been studied by Mlinarić and Ponikvar [8]. The railway system's main components are infrastructure, traffic management and rolling stock. The authors highlighted that the railway system is a collection of different components, and it is necessary to combine them all to rationalise the energy consumption of railway lines, from optimising the parameters of infrastructure and stations to energy savings during the operation phase of the movement. Mlinarić and Ponikvar [8] concluded that upgrading the railway infrastructure, reconstruction of the stations and construction new segments of railway lines will be costlier and will take longer than working towards to save energy consumption during the operational stage. The railway operators face a dilemma of which of these two solutions will contribute the most to improving the energy efficiency of railways.

To solve this dilemma Paulussen et al. [9] developed a new universal method based on energy efficiency, individual rolling stock performance, rolling stock performance in networks and an operational stage. The authors concluded that the cheapest way and in a shorter period to improve the efficiency of energy consumed by railway lines would be the reduction of energy consumption in the operational stage of rolling stock. The energy rationalisation will reduce the cost of transportation and the environmental impact, which in turn will increase the competitiveness of the railways towards other modalities.

Gunselman [10] overviewed several possibilities to increase the energy efficiency of electric railway systems. The author looked at a different technological solution that can reduce energy consumption by electric railway vehicles. Such as reduction of braking loss, optimisation of speed profile, prevention of route conflicts, energy-optimised timetables, and energy storage. Special attention has been given to the energy storage that can be installed in existing and a new DC substation to store the surplus braking. The author pointed out that reducing the vehicle's weight is one of the crucial factors for energy consumption. This statement was analytically confirmed in this paper.

The difference and connection between energy consumption and energy efficiency were mathematically described by Pan, et al., [11]. The authors concluded that energy efficiency improvements could be achieved by increasing the load ratio and decreasing the train weight. Also, increasing the load ratio will support more efficient use of infrastructure.

Ćwil, et al., [12] pointed out the lack of progress in reducing emissions by railway transport in some countries. However, in several countries, for example, the Netherlands railway reached zero-emissions level. The authors studied the factors influencing the energy consumption of running trains and attempted to establish the difference in energy consumption between different railway vehicle types in Poland. The energy consumed by trains strongly depends on the number of stops. Since accelerating the train is high energy consumption. The authors found that one of the differences in energy consumption between trains included in the research reached more than 20%. Our study looked at differences in the construction of HSRS and extended research by Ćwil, et al., 2021 to determine the factors that influenced the difference in energy consumption of the selected HSR systems.

De Martinis, V. and Corman, F. [13] discussed the potential of collected data for decreasing energy consumption in railway systems. With the introduction of real-time sensors in railways worldwide, a massive volume of data has been collected. The vast volume of data gives new information on the operation of railway systems, contributing to new technological developments and improvements in energy efficiency. The authors pointed out that energy consumption mostly comes from the traction system that keeps vehicles moving. Nevertheless, vehicle design plays an important role also. The lighter and newer vehicles with higher energy efficiency will consume less energy.

Zarifyan, A. et al. [14] studied the energy efficiency of the traction system of railway vehicles. The authors used computer simulation to show that when a freight vehicle operates with partial load, there is the possibility to regulate the locomotive power using each axis individually. They found that the reduction of energy consumption can be as significant as 16.8%. These results show that a train's energy consumption depends on the vehicle's loading coefficient. The importance of maximising the load of high-speed rolling stock to increase energy efficiency has been confirmed in the present paper.

3. Materials and Methods

3.1 Research Data

Most of the data is drawn directly from International Union of Railways (UIC) statistic websites and used in research from 2010-2017. The data can be classified as reliable. Some data for specific periods were missing, and, in this case, the average statistics were used. The selected HSR systems are in the following countries: Japan (JP), South Korea (KR), Germany (DE), France (FR), Italy (IT), Spain (ES), and Turkey (TR). The two-letter code for countries it is an international two-letter code based on ISO 3166-1. These abbreviations were later used in the construction of graphs and tables. The total power consumption by electric tractive stock for selected operators and the number of passengers and passenger-km have been extracted from Railisa UIC Statistics for 2010-2017. UIC statistic website “is an online tool allowing users to visualise and download data provided by railway companies worldwide…an available number of indicators such as length of lines, passenger and freight traffic, train movements, rolling stock, staff numbers, financial results, etc…” [15]. Due to the lack of complete data for 2017 for Japan and Italy, approximate revenue-earning high-speed traffic (total number of passengers) has been calculated. The UIC Statistic website Railisa provides data on revenue-earning high-speed traffic by the operator, but in this research, we investigate the performance of HSR overall by country. To obtain data on the HSR network by country, we summarised high-speed traffic revenues by the operator by year. In connection with this, there may be a discrepancy with actual values. In analysing the efficiency of the selected HSRs, the average traction power was taken into consideration. It will help capture the differences in railway transport technology and how it affects the technological productivity of HSR.

3.2 DEA as A Method to Evaluate Efficiency of HSR Systems

The environmental problems are expected to rise steadily, which is a significant concern. To be sustainable, a global population, on average, must produce no more than 2.0 tonnes of CO_2 per person, but currently, it is around 4.0 tonnes per person [16]. Developing a new, greener rolling stock and improving existing ones will reduce the use of fossil fuels, which will reduce the CO_2 emissions produced by railways.

In 2011, UIC published a “High Speed Rail and Sustainability” report, showing that HSR is the most environmentally friendly mass transportation mode. Even consider externalities produced by the construction of infrastructure and rolling stock. Sustainability for railway companies “means to meet the expectation of society and customers and sustain business by responsible leadership” [17].

The ten sustainable development principles for railways were published in 2016 by RSSB. They reflect the challenges and opportunities the railway industry can bring to society without compromising the future quality of life [18]. These principles cover the economic, environmental, and social sustainability of railways. Despite having the same principles, all HSRs perform differently. Some of them are more successful than others.

The Data Envelopment Analysis (DEA) has been used to benchmark the selected HSR. Emrouznejab et al. [19] produced a bibliography of articles related to DEA, which have been published since 1978. They found that interest in DEA methodology had proliferated in the last three years and reached approximately 1000 articles published every year.

Growitsch et al. [20] analysed 54 railway companies using DEA to find out how the regulatory environment affects the economic performance of European Railways. Amiril et al. [21] found that 27 sustainability factors cover the performance of transportation infrastructure projects. They can be divided into environmental, economic, social, engineering/resource utilisation and project management performance factors [22].

Efficiency and effectiveness in railway performance applying a DEA model was studied Yu et al., [23]. They selected 20 railways for the year 2002. Because they selected only one year, the results can be influenced by external causes that are not under railway control. The productivity growth in European railways was studied by Loizides et al. [24]. They investigated ten railroads in the EU from 1970 to 1992. It was found that technological changes declined over time and only German and British railways had a positive technical change.

Regarding the DEA approach, only one research has been found that compares the sustainability of HSRs. Doomernik [25] benchmarked eight HSRs’ performance between 2007 and 2012. The author investigated production and service efficiency and identified the most efficient high-speed railway systems. A substantial distinction in performance was found between railways in Asia and Europe and a considerable difference within these regions.

Data Envelopment Analysis (DEA) is a method that measures the efficiency of similar Decision-Making Units (DMUs) [26]. The DEA is a non-parametric method based on the assumption that the production function of fully efficient DMUs is not known [27]. The DEA was proposed in 1978 by Charnes, Cooper, and Rhodes. This method is more appropriate for evaluating the efficiency of HSRs as input values do not vary substantially over time [28]. In this research, HSRs are Decision-Making Units. The DEA defines the relationship between the outputs that the HSRs can produce and the inputs and aims to estimate the relative efficiencies of HSRs. Cook et al. [29] concluded that the number of DMUs must be at least twice the number of inputs and outputs combined.

This DEA analysis has been acknowledged before to benchmark the performance of decision-making units (DMU) and find the best practice. The efficiency of DMUs depends on their distance to the frontier. This methodology uses the ratios between outputs and inputs and compares all units and their relative efficiency concerning the best performing unit. The efficiency score (1) for units is defined as the weighted sum of multiple outputs, $\sum_{k=1}^{r} UkYkj$ divided by the weighted sum of multiple inputs $\sum_{i=1}^{m} ViXij$ [30].

$$\max h_j = \frac{\sum_{k=1}^{r} UkYkj}{\sum_{i=1}^{m} ViXij} \tag{1}$$

Where: h_j, is the maximum ratio of outputs to inputs, k = 1…. r is the sum of k-th positive output and i = 1…m is the weight i-th positive inputs.

The function that presents maximum output is achieved from a given level of input called output-oriented function.

An advantage of applying the DEA is that it can operate with multiple inputs and outputs and is not needed to clarify their importance. Other advantages are that it is suitable for small samples and short run time [31]. The DEA compares each of the selected HSRs with all others and identifies HSR operating inefficiently and finds the target values of output and input for inefficient railways. The efficiency is defined as the ratio of the output to input, and this ratio must be equal or less than 1 (or 100%). If the ratio is equal to 1 (or 100%), it points to the most efficient HSRs [22].

The CCR model is named after its developers Charnes, Cooper, and Rhodes [30]. The CCR model assumes constant returns-to-scale (CRS). For this research, the input oriented CCR model has been applied. The input-oriented model means that outputs will be kept constant, but inputs must be reduced to reach the frontier line. To evaluate the efficiency of the selected HSR systems one input has been selected: a total power consumption by electric tractive powered stock for the selected operators and two outputs: the number of passengers and passenger-km.

4. Study of Rolling Stock for the Selected HSRs

HSRS can be divided into two groups. The first group is long life HSRS with the renovation, and the second group is HSRS with short life without renovation. In Japan, HSRS was designed for a 15-20-year life cycle. In Europe, it is around 30 years [32]. Because of this, HSRS in Japan does not need to go through a significant renovation within its lifespan. Shorter lifespan rolling stock will allow faster implementation of new technologies, have more modern trains, and revitalise the railway manufacturing industry. The largest rolling stock manufacturers in Europe are Alstom, Siemens, CAF, Stadler and AnsaldoBreda, in Canada Bombardier, in China CRRC [33].

RS (Rolling Stock) of the selected HSRs have different technical characteristics and capacities. In Europe, the width of HS trainsets varies between 2750 mm to 3000 mm. In Japan and South Korea, it reaches 3380 mm, and in Turkey, it is 2924 mm [34]. In Europe, the new build HSR operated with a UIC GC loading gauge, 3150 mm width and 4650 mm high. In Japan, it is 250 mm wider. The wider loading gauge allows increasing the capacity of seats for HSRS. In Japan, HSRS has five seats per row, but in Europe, only four seats. The wider train, which can accommodate 2+3 seats in rows, have 25% more capacity than a train with a standard car body [35]. Also, the number of seats on the train depends on the proportion of first-class accommodation, a restaurant car, and whether it is a single or double-decker train. Distributed powered trains have a higher capacity of seats than trains with a concentrated power system. Table 1 compares selected HSRs in terms of used RS and their technical characteristics. Data were taken from the UIC website [34].

Table 1 Technical characteristics of HSRS in selected countries, Uic.org., (Calculated by Author) [34].

Country	**Operator**	**Train Sets (number)**	**Average Traction Power (kW)**	**Max Operational Speed (km/h)**	**Axle Load (ton)**	**Total number of seats**	**Average Capacity of Train (seats)**
France	SNCF	408	8770	320	17.0	193734	475
Germany	DB AG	280	7000	320	14.2-18.0	139881	500
Italy	FS	182	7800	300	15.1-17.0	89441	440
Spain	Renfe	229	6100	300	16.0-18.0	69291	241
Japan	JR	405	12000	300	11.4-16.0	381019	950
Turkey	TCDD	19	7200	300	17.0	8276	424
S. Korea	Korail	144	10200	300	17.0-N/A	81975	560

The traction power of HSRS varies between 11 kW to 24 kW per tonne [2]. There are two types of HSRS in power distribution: distributed power system and concentrated. The modern HSRS more often has a distributed power system. This type of HSRS has better traction performance, have higher capacity, and lower axle load. However, some HSRs, for example, in France and South Korea, operated only HSRS with a concentrated power system. In Japan, all High Speed (HS) trains have a distributed power system. The first HSR line in the world is Japanese and named Shinkansen. The line was opened on 1 October 1964, and now it integrates several HSR lines in one network with the same name, Shinkansen. N700-2000 is one of the latest Shinkansen trains that can be formed from 16 cars (14 motor coaches and two trailer coaches) with a capacity of 1323 seats [34]. The reduction of energy consumption by HSRS can be achieved by reducing the mass of train per seat and increasing the number of seats per train metre [36].

The maximum length of trains in Japan is the same as in Europe, 400 metres. With increasing the length of noses of HSRS, will be a decrease in the train's capacity. To optimise the capacity of electrical multiple units (EMUs), the nose of trains should be as short as possible [34]. In the current situation when modern society is fighting with COVID 19, and "social distancing" having been implemented on public transport, the capacity of trains has been reduced dramatically. In Europe, before COVID 19, the inter-city HS trains on average had 2-2.4 seats per metre of a train, a double-decker approximately 2.8 seats per metre of train and in Japan 3.3 seats per train metre [35].

One of the essential technical characteristics of HSRS is an axle load. In Japan, the majority of RS has an axle load between 11 and 13 tons, but 20 train sets class E4, which went into operation in 1997, has a maximum axle load of 16 tons [34]. In Germany and Spain, the maximum axle load for HSRS is 18 tons. EMUs with distributed power systems have lower individual axle loads. In France, the axle load has been restricted to 17 tons/axle that will extend track formation life and increase the speed of trains. Minimising the axle load will reduce infrastructure and other structural maintenance, reduce construction costs, reduce the noise level, reduce energy consumption, and increase speed. The higher average speed of HSRS leads to better route utilisation and higher productivity. The rolling stock manufactures need to look for technical solutions to minimise the axle load. Table 2 shows the types of HSRS that operated in the selected countries.

Table 2 Type of HSRS in selected countries in 2019, Uic.org., 2020 (Calculated by Author) [34].

Country	Ratio Pass-km/seat	Ratio mass/seat ton/seat	Average Age (years)	Distributed Power	Concentrated Power	Articulated	Tilting	Double Decker
France	0.181	0.777	21	---------	408	408	------	270
Germany	0.224	0.997	19	177	103	-------	75	--------
Italy	0.204	1.011	17	123	59	25	73	--------
Spain	0.268	1.041	14	115	114	114	90	--------
Japan	0.300	0.515	13	405	---------	-------	268	20
Turkey	0.145	0.816	6	19	---------	-------	-----	-------
S. Korea	0.266	0.912	10	---------	144	144	-----	-------

Some HSRs operate double-decker trains, which can double capacity with the same staff. These trains have lower consumption of energy per seat. Examples of this trend can be found in France. The downside of this type of train is that it has reduced accessibility for passengers with restricted mobility. These trains have higher axle load and weaken resistance to crosswinds. The wide-body and double-deck HSRS have more seats per train metre [36].

One of the most critical developments in the construction of TGV-PSE in France was the introduction of articulated suspension between passenger vehicles, also called "Jacobs bogies". A traditional coach has two bogies, and each bogie has two axles; on TGV-PSE trains, each bogie supports two coaches. Using this innovation reduces the weight of the train as the bogie is one of the heaviest components, decreases the level of noise from the train, improves passenger comfort and reduces the bogie maintenance. The downside of articulated trains is increased axle load, lower capacity, and complex maintenance of articulated trains. The car length of an articulated train is 13-19 m, non-articulated car length is approximately 25 m [34]. This type of train is widely used in France, South Korea, Spain, and Italy.

The new articulated high-speed train AGV from Alstom has a reduced weight and needs 15% less energy than TGV [37]. Power output for high-speed trains also depends on a train formation. Trains can have different formations from 16 or eight cars, as has Shinkansen Series 500 and Shinkansen Series 700 or the seven cars trainset (trainset consists of 4 motor coaches and three trailer coaches) of Italian operator Frecciarossa. Some trains are more flexible in formation. An AGV can be formed from 7, 8, 10, 11 or 14 cars. Trains that have distributed traction power and are equipped with articulated technology have reduced mass per seat [36]. In Spain (Table 2), from 114 articulated trains, 90 are also equipped with tilting technology.

Tilting technology can be an alternative to building new tracks or straightening existing ones. The tilting technology allows to pass curves at higher speeds and not reduce the riding comfort for passengers. The tilting technology prevents passengers from having some discomfort from the lateral acceleration. Also, it is much cheaper than having to build new tracks. This type of technology allows the train to have higher speeds in curves that, in turn, can reduce the journey time. This system reduces the travel time, but it increases the risk of overturning [38].

Most modern HSRS are made from aluminium, aluminium alloy, carbon steel and stainless steel. Aluminium car bodies reduce trains' weight, give raw material saving, and reduce energy consumption to operate trains [39]. Replacing steel with aluminium can achieve a weight reduction of the car body of a train between 20-30% [40]. Reduction of rolling stock mass has a significant impact on energy reduction by railway system [41]. Aluminium is easy to recycle, and it does not lose its quality after recycling. Table 3 shows the HSRS in the selected countries regarding power systems, axle loading and car body materials.

Table 3 Comparison of different types of high-speed trains in terms of power systems, axle loading, and car body materials (Created by Author, the data taken from various sources).

Country	**Main Constructor**	**Train**	**Power system**	**Axel Loads (ton)**	**Car Body**
France	Alstom	AGV	Centralized	17	Aluminium with Carbon
Japan	Hitachi	Shinkansen-Series 0	Distributed	16	Carbon Steel
Japan	Hitachi	Shinkansen-Series 700	Distributed	11.4	Aluminum alloy
Spain	Talgo	Talgo 350	Centralized	17	Aluminium
Italy	Hitachi Rail Italy	ETR1000	Distributed	17	Aluminum alloy
Germany	Siemens	ICE1	Centralized	19.5	Aluminium-silicon alloy

Germany	Siemens	ICE2	Centralized	19.5	Aluminium-silicon alloy
Germany	Siemens	ICE3	Distributed	15	Aluminium
South Korea	Hyundai Rotem	KTX-Sancheon	Centralized	N/A	Aluminium
Turkey	Simens	HT80000	Distributed	17	Aluminium

The aluminium car bodies have some disadvantages, such as the increase in maintenance costs and a need to consider the insulation properties as they can be less effective than when a steel car body is used. New high-speed trains have an aluminium body but, in the future, there is a significant potential to use carbon-fibre-reinforced polymers (CFRP) for train car bodies. Using CFRP can reduce more energy at the operational stage than using aluminium. Operating the lightweight HSRS will result in fuel reduction and increased speed. As a result, it will decrease CO_2 emissions into the atmosphere and increase the capacity of HSR corridors. The replacement of six chief parts of HSRS by CFRP can reduce weight by 24.61% [42]. To reduce energy consumption is essential to reduce the mass per seat, which will reduce the energy lost in braking and increase the size of a car body to accommodate a more significant number of seats [36].

5. Energy Consumption of Rolling Stock

Electrified railways are one of the most energy-efficient modes of transportation. The energy consumption of a high-speed train depends on several factors, including the geometry of a line, operational strategies, and technical characteristics of a train. The energy needs a tractive effort to move the train and for auxiliary systems of the train. Several solutions can reduce energy consumption by railway transport, such as modernisation of power systems and the use of energy storage, modernisation of rolling stock and implementing a new generation of control and automation equipment.

Applying energy-efficient railway design strategies will help decrease energy consumption by a railway system. The geometry of railway lines has a significant influence on train energy consumption. The reduction of the longitudinal gradients and curvatures can support the reduction in energy consumption. A train that moves at a higher speed uphill consumes more energy than would be driven in the same condition but at a slower speed, increasing running time. Braking followed by acceleration also increases energy consumption [8]. The more frequent acceleration and braking will lead to higher energy consumption [43], but coasting will lead to energy saving [9]. It was estimated that smooth driving could reduce energy consumption by 12% [10]. The development in regulations on speed profile optimisation by determining the optimal switch point from one control mode to another will lead to a decrease in energy consumption.

Figure 1 shows the train operational profile on long distances between stops. It will be acceleration on short distances between stops–coasting–braking to stop. The braking stage includes the regenerative and non-regenerative braking measures to reduce a train's speed. After the speed was reduced to 10-15 km/h, the mechanical brake only is used to complete stopping [44].

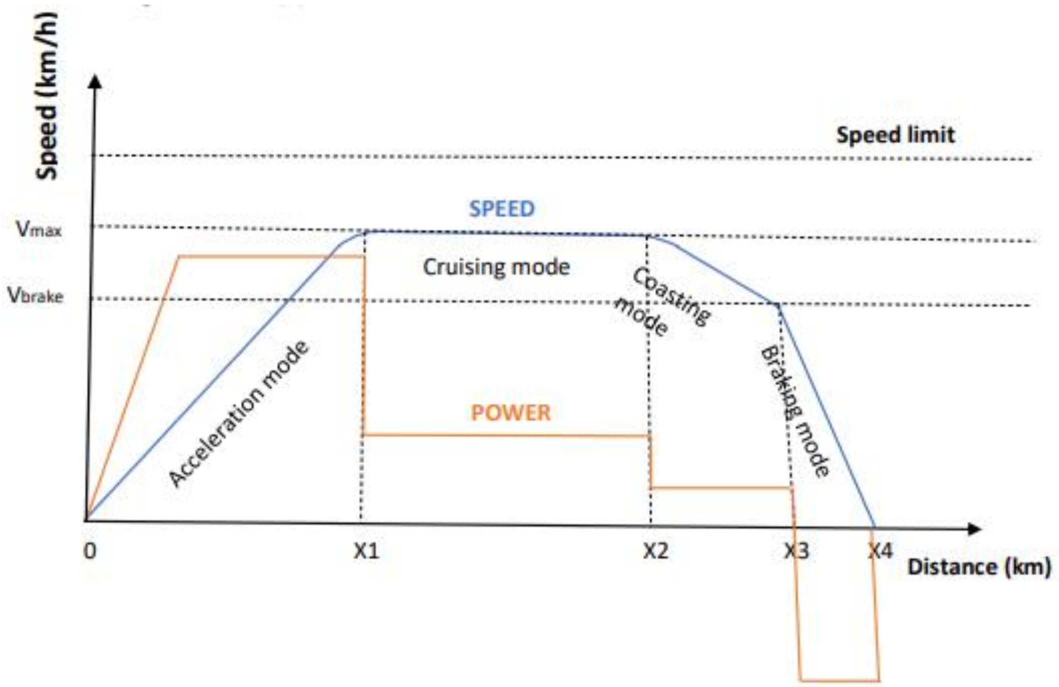


Figure 1 Speed-distance train operation profile for long-distance (Created by Author).

The driving regimes, including the switching points,

- X1: switching point of acceleration to cruising,
- X2: switching point of cruising to coasting, and
- X3: switching point from coasting to braking.

From starting point 0 and when a train is running on acceleration mode to point X1, the train uses the full power, but the train cannot exceed the speed limit for safety reasons.

There are four driving modes. From stop to point X1, a train accelerates on full power to reach V maximum as quickly as possible. From point X1, a train runs at the target speed to point X2 and uses partial power. From point X2, the train runs in the coasting mode to point X3; the train moves due to inertia energy and consumes only minimal energy. Decreasing the cruising speed and introducing coasting is one of the easiest ways to reduce energy consumption [45]. Modifying the driving modes or changing the running speed can develop energy-efficient timetables. From point X3 and before point X4, where the train stops, it becomes a generator of energy if it uses the regenerative braking system. It was found that a 10% increase in driving time can reduce energy consumption by up to 25% [10]. Optimisation technologies can be used to balance trip duration and energy consumption minimisation.

The power emitted from the substation does not fully reach the train. There are losses during transformation and transmission. The lines electrified at a higher voltage have lower losses during the transformation and transmission of the energy from the power station to the train. For trains on lines electrified by 3 kV DC, it is necessary to produce 22.6% more energy than the energy received by a pantograph. For lines electrified by 25 kV AC, it is necessary to produce only 8% more energy than received by a pantograph [46]. The greater energy consumption by the train, the greater the losses in the transformation and transmission [47]. Reduction of electricity losses in rail electrification systems will improve energy efficiency.

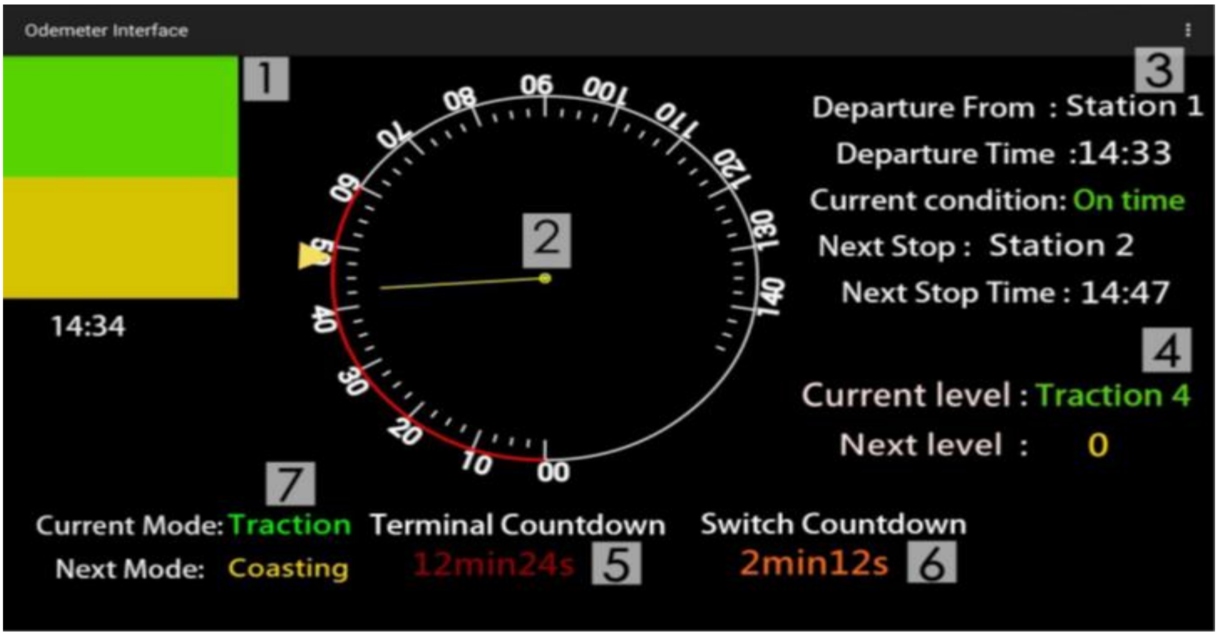
Improving the operational strategies is less costly than improving infrastructure or rolling stock. Operational strategies such as coasting can sufficiently increase energy efficiency, but the combination of coasting and regenerative braking will further increase energy efficiency [9]. Every braking in front of a station's entry signal will increase energy consumption. So, the number of stops has sufficient influence on the train's energy consumption.

The energy-efficient rolling stock is one of the main conditions in the reduction of energy and CO_2 emissions. The operational stage of the life cycle of rolling stock accounts for more than 80% of environmental impact [48-50] and reduction in energy consumption will lead to a decrease in CO_2 emissions. The technical characteristics of the train include maximum speed, weight, power output. They will also influence the train's energy consumption.

The consumption of energy is related to the driving technique employed by each train driver. There are several driving techniques to optimise energy consumption. One of the energy-efficient driving techniques is an eco-driving technique. This strategy aims to optimise train speed profile and maximise the coasting phase to minimise energy consumption, reduce operational costs, and reduce environmental impact. The eco-driving technique can save up to 21% of the energy and optimise the running time [44].

The next step to optimise the energy consumption by train was the introduction of the Driving Advisory System (DAS). On-board DAS calculates an energy-saving profile based on a railway line's real-time operational condition. DAS increases the capacity of a line, optimises an energy-efficient trajectory, and improves the punctuality of a train [51].

Figure 2 shows the interface of DAS, which consists of seven sections. Most of them are signal lights ahead, speedometer, essential timetable information. The train driver can modify the train's motion regarding the information supplied by DAS in real-time. The driver can increase the speed to recover the delay or reduce the speed to save energy.



14:34

Departure From : Station 1
Departure Time :14:33
Current condition: On time
Next Stop : Station 2
Next Stop Time : 14:47

Current level : Traction 4
Next level : 0

Current Mode: Traction
Next Mode: Coasting

Terminal Countdown
12min24s

Switch Countdown
2min12s

Figure 2 Main interface of DAS Source: [51].

Another way to improve the energy efficiency of railways is through the optimisation of braking energy. A train can feed up to 40% of the consumed energy back to the grid using a regenerative braking system [10]. However, it is not easy to coordinate all trains so that there would be a complete energy exchange between braking trains and accelerated ones. Reduction in the losses of regenerative energy will further improve energy efficiency. The new generation of energy storage such as supercapacitors, Li-ion batteries and flywheels can effectively store the surplus of regenerative energy. It can be an on-board storage system or wayside energy storage [52]. The wayside storage stores the electricity recovered from regenerative braking that can be used by the next accelerating train. The on-board storage system will collect the recovered electricity for a train to be used later.

The main disadvantage of electrochemical batteries is their short lifetime compared to RS. The supercapacitor offers a high-power capacity, fast to charge, high efficiency and a long cycle lifetime that ranges from 100.000 to a million cycles [53]. The supercapacitor can reduce catenary energy consumption by 23.6%, Li-ion battery by 22.9% and flywheel by 23.7%. The on-board energy storage can save more energy than any other energy-saving measure [54].

The amount of energy consumed by a train consists of the energy required by traction units and auxiliary systems. The auxiliary systems require a considerable amount of energy for heating, ventilation, and lighting of RS. The great potential in energy savings can be achieved by improving the thermal isolation of car bodies, updating air-conditioning equipment to be more efficient, and using LED for the interior illumination of vehicles. The intelligent air-conditioning system which controls temperature and CO_2 concentration can reduce energy consumption by 11% [10]. To reduce the amount of energy needed for auxiliaries, the on-board photovoltaic system (PV) located on the roof of the train can be employed. This system uses the energy from the Sun to generate electricity, and it can be integrated with the electric power supply to power the train [55].

HSRS must meet several criteria, such as efficiency, safety, and passenger expectation. The essential tools aiming to reduce energy consumption and improve energy efficiency by RS were analysed in TOSCA (Technology opportunities and strategies towards climate-friendly transport), a project of the European Commission [56]. In the short term, the improvements of the RS and operating it most sustainably can substantially reduce energy consumption by the railway industry. It is less expensive than building new or upgrading existing railway lines. Some of the tools that will help to make railway transport greener regarding the rolling stock are:

- Improving the aerodynamic performance of a train body and pantograph. For HSRS, the shape of the front section has an essential effect on the aerodynamic resistance. With an increasing speed, it increases aerodynamic travel resistance. Improving the aerodynamic of HSRS can reduce energy consumption by up to 15% [44].
- Reducing a train mass is one of the crucial factors in reducing energy consumption. The weight of a car body can be reduced by applying new technologies and materials.
- Regenerative braking is when trains consume the energy and operate as producers. The energy produced by regenerative braking can be directly sent to the railway supply system to be consumed by other trains; it can be stored for future use or sent to the primary grid. The regenerative braking system coupled with energy storage equipment (ESE) will be more energy efficient. ESE can be installed on-board the train or on existing or new built electrical wayside substations [57].
- Increase the train's capacity, as kilometres of vacant seats decrease the energy efficiency. The Railway operators need to be more flexible with the size of trains. Consider using smaller units of RS if demand decreases.

- Adapt new operational and behavioural approaches (Eco-driving), implementing of Driving Advisory System (DAS)
- Improve the energy efficiency of non-traction equipment by updating equipment to a more efficient use such as intelligent air-conditioning system and LED for the interior illumination of vehicles.

The energy efficiency of RS is a significant factor in creating a sustainable railway system. The differences in energy consumption between selected HSRs have been studied. For this research, seven HSRs were selected for 2010-2017. The selected HSRs differ in energy consumption, achieved the number of passengers, passenger-km, and seat utilisation. This research calculates, analyses, and benchmarks the performance of the selected HSRs and investigates some of the factors that can influence the efficiency of HSRS in terms of energy consumption.

6. The Main Findings in Benchmarking the Selected HSR in Terms of Energy Efficiency

In defining the variables set to be testing, reference was made to several previous papers that analysed the inputs and outputs to evaluate the rail efficiency. The data represents a mix of variables used in relation to capacity, service, and environmental measures. Also, consideration was influenced by the availability of reliable data. Zhou et al. [58] concluded that the most popular environmental input is energy consumption.

The efficiency score shows the possibility of HSRs to produce given output with a minimum input that is measured by output/input ratio. The efficiency of HSRs compared with efficiency levels of other HSRs. The efficient HSRs are those that attain an efficiency frontier and has efficiency score = 100%, inefficient HSRs are identified by a ratio of less than 100%. Table 4 shows the efficiency scores of DEA CRS input-oriented model for selected HSRs in period 2010-2017 by year.

Table 4 Efficiency score of DEA CRS input-oriented model for selected HSRs in period 2010-2017 by year (%) (Source: Author's creation).

Period	KR	ES	DE	TR	FR	IT	JP
2010	47.23	37.77	21.34	18.68	56.35	22.03	100
2011	48.20	33.25	19.49	24.76	51.20	24.03	100
2012	51.89	30.99	19.78	34.17	48.21	24.99	100
2013	50.58	35.43	21.16	49.96	48.15	23.28	100
2014	50.12	35.07	20.87	58.21	48.75	22.59	100
2015	47.23	35.97	20.32	62.88	52.17	21.33	100
2016	42.14	37.70	21.88	56.57	55.96	20.21	100
2017	37.69	38.18	23.03	65.82	59.57	19.82	100
Average	**46.89**	**35.55**	**20.98**	**46.38**	**52.55**	**22.29**	**100**

Table 4 shows that JP HSR is the most energy-efficient in the selected group of HSRs. The less energy-efficient is DE HSR, which needs to reduce the total power consumption by electric tractive stock and auxiliary system on an average of 79.12% but carry the same number of passengers and passenger-km. Inefficient HSRs can improve their efficiency by reducing their level of input. The efficiency score for the selected period for all selected HSRs floated around 5%-7% increased or decreased apart from TR HSR. For TR HSR, the efficiency score increased from 18.68% in 2010 to 65.82% in 2017. It can be explained that the first HSR in Turkey went into operation in 2009, and ridership gradually increased from 2.5 million in 2011 to 5.7 million in 2015 and continues to increase [59].

To investigate the effect of different types of HSRS on the energy efficiency of the selected HSRs, the ratio weight per seat and seat utilisation of high-speed rolling stock has been calculated. To statistically analyse the results of the DEA approach and the selected variables, the IBM-SPSS Statistics software has been applied.

The scatterplot has been used to analyse the relationship between energy efficiency scores, weight-seat ratio, and seat utilisation ratio. Figure 3 shows the scatterplot's energy efficiency score and weight/seat ratio; the selected variables are negatively related linearly. The energy efficiency scores decrease with increasing the weight/seat ratio.

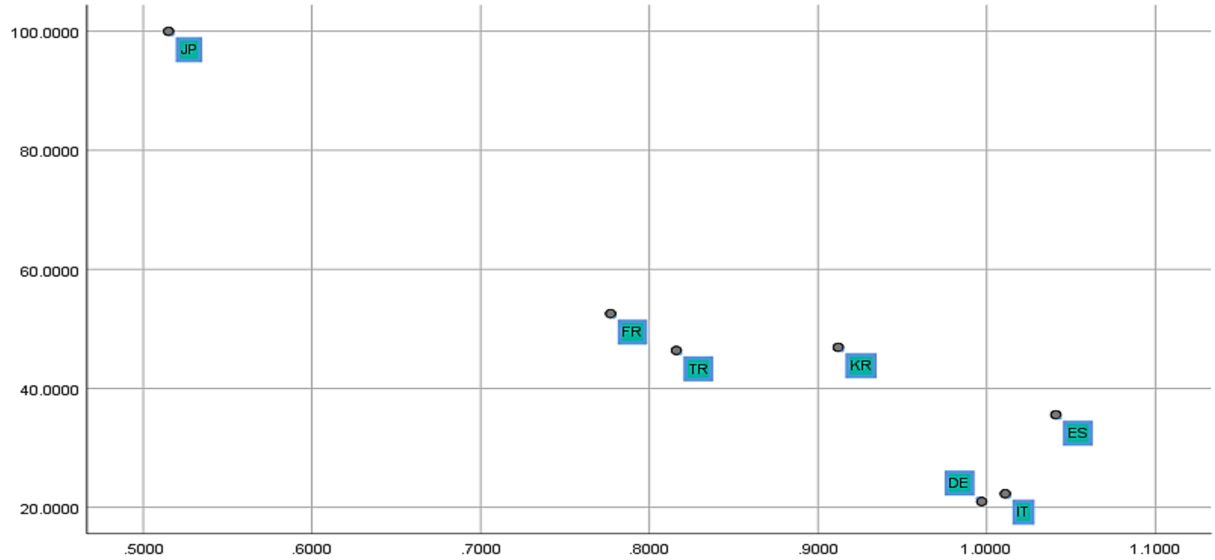


Figure 3 Scatterplot of energy efficiency scores and weight/seat ratio weight per seat ratio.

The value of the Pearson correlation coefficient can vary between -1 to +1. The value of -1 indicated perfect negative correlation, the value of +1 indicated perfect positive correlation and the correlation of 0 means that there is no relationship between variables [60]. Table 5 shows the strong negative correlation between efficiency score in terms of used energy and weight/seat ratio. The seat utilization ratio has a strong positive correlation with energy efficiency. Increasing the ratio of seat utilization increases the energy efficiency score. The increase in the weight/seat ratio decreases the energy efficiency score. The correlation is statistical significance at the traditional probability $p < 0.01$ level. However, the statistical significance has not reached statistical significance at the traditional $p < 0.05$ level, the size of the sample is low (N = 7).

Table 5 Correlation between energy efficiency scores and weight/seat ratio and seat utilization.

	Energy	Weight	Utilization

Energy	Pearson Correlation	1	-0.951^{**}	0.585
	Sig. (2-tailed)		0.001	0.167
	N	7	7	7
Weight	Pearson Correlation	-0.951^{**}	1	-0.657
	Sig. (2-tailed)	0.001		0.109
	N	7	7	7
Utilization	Pearson Correlation	0.585	-0.657	1
	Sig. (2-tailed)	0.167	0.109	
	N	7	7	7

**. Correlation is significant at the 0.01 level (2-tailed).

Testing the Pearson correlation coefficient has been following a guideline [60] that states that the strength of the relationship is small r = 0.10 to 0.29; medium r = 0.30 to 0.49; large r = 0.50 to 1.0.

7. Analysis and Discussion

To analyse the performance of HSRs in terms of energy efficiency, the seven HSRs have been selected. The operational stage of HSR is the most energy consuming. To increase energy efficiency by HSRs, different types of trains have been designed. Trains are getting longer, wider, and higher. By applying the DEA approach, it has been found that Japan HSR is the best performer in the selected group. Japan HSR is the most energy-efficient, and German HSR is the least energy efficient in the selected group of HSRs.

To further investigate the difference in HSRs performance, the IBM SPSS software has been applied. The results of IBM SPSS show a robust negative correlation between the energy efficiency scores and to weight/seat ratio and a strong positive correlation between energy efficiency scores and seat utilisation ratio. The German HSRS shows one of the lowest weight/seat ratios. Only Italian and Spain HSRS have a lower weight/seat ratio. It is one of the reasons for a low energy efficiency score by German HSR. Also, the average age of HSRS for Germany is 19 years old. It is one of the oldest fleets of HSRS in the selected group. From 280 trains, 103 have concentrated traction power systems.

The highest energy efficiency score in the selected group of HSRs has been recorded for Japan HSR. It can be explained that Japan HSRS has the lowest weight/seat ratio. HSRS in Japan is on average 13 years old, and all fleet of HSRS has distributed traction power system.

The correlation is strong and positive in terms of the relationship between energy efficiency scores and passenger-km per seat. The increasing number of passenger-km per seat increases the energy efficiency score. It is an important finding which shows the importance of seat utilisation for increasing the energy efficiency scores by railways. It can be achieved by increasing the occupancy of trains and increasing train utilisation. The highest ratio score P-km/seat has Japan HSR and the lowest HSR in Turkey. It shows that Japan HSR has the highest level of HSRS utilisation in the selected group of HSRs. The HSR in Turkey has the most modern HSRS with an average age of six years, and this can be one of the reasons that the energy efficiency score of HSR in Turkey is higher than in Germany, Italy, and Spain. Also, HSRS in Turkey has distributed traction power system, and car bodies are built with aluminium.

8. Conclusions and Recommendations

There is increased pressure from society to minimise the energy consumption by the transport industry, reduce the operational costs and environmental impact. There are many ways to achieve the targets for sustainable mobility. Such achievements can be made possible through more significant technological improvement and increased passenger seat utilisation. The train operators, manufacturers, and public authorities need to work towards greener transport whenever economically sensible.

A decrease in vehicle mass, improved design of HSRS and increased occupancy of trains will support the reduction of energy consumption by HSRS and, as a result, will improve the energy efficiency of the railways. Reducing the axle load will minimise infrastructure maintenance, increase speed, and reduce energy consumption.

The main aim of this research was to look at factors affecting the difference in energy consumption of the selected HSRs systems. Rolling stock design can affect energy consumption. Analysis of selected HSRs shows that energy efficiency scores are higher for HSRs that employ trains with a distributed traction power. Reducing the axle load is the most critical factor in increasing the speed of trains and reducing energy consumption. Reduction of mass per seat will reduce the energy lost in braking. It can be achieved by introducing the articulated railcars and using a new lighter material. To increase the passenger-km carried per unit of energy, there is a need to consider the number of seats. Instead of having locomotive and passenger cars, these can be replaced by electric multiple units (EMU). The energy efficiency scores of the selected HSRs positively correlate with the utilisation of seats. The full load rate is an essential factor that influences energy efficiency. The higher utilisation of seats will require fewer trainsets, will lead to increases in productivity of an operation, increases in the capacity of the line, and reduction in energy consumption. Using more advanced rolling stock can increase speed and reduce energy consumption.

This research highlighted important facts of energy efficiency for HSRs at the operational stage and extended the existing knowledge in the field of energy consumption by HSRs. The research found the factors causing differences in energy consumption for the selected HSRs. Train operators need to purchase less energy-consuming RS to provide a sustainability boost. This research can support train operators to make decisions when acquiring new trains and assess the benefits of acceleration in the modernisation of the current RS. Climate change will influence the energy efficiency of railway systems. Further work is recommended by widening the scope of data and benchmarking the train types by the total energy consumption between different seasons rather than total power consumption by railway operators.

Author Contributions

Study conception and design, collection data, analysis and interpretation of results , draft manuscript preparation by Dr Watson. Dr Ali and Dr Bayyati guided and encouraged this study.

Competing Interests

The author has declared that no competing interests exist.

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