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Possibility to use a dual-drive locomotive type 111DE for passenger transport in the territory of Poland

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Abstract. The vast majority of passenger rail transport in Poland is carried out by vehicles powered by electric traction. In case when a train needs to pass through a non-electrified section of the line, it is necessary to use an electric traction-independent vehicle, which, translated into the current situation, means using a vehicle with an internal combustion engine. The authors propose using a dual-drive 111DE locomotive for passenger rail transport, which can move on electrified and non-electrified railway lines. The article also presents data on the railway infrastructure and statistics on passenger rail transport in Poland. Considerations and justification for the use of a dual-drive vehicle are presented.

Keywords: passenger transport, dual-drive locomotive, rail transport

1. Introduction

According to Statistics Poland [1], 19,422 km of railway lines were operated in Poland in 2020. In the case of the line type, electrified lines accounted for 62.6% (12,149 km). The rest are lines without suspended electric traction, meaning only vehicles with their independent power source can move on them. In practice, only vehicles equipped with diesel traction can run on 37.4% of railway lines in Poland. Additionally, the degree of electrification in the country varies considerably and depends on the voivodeship. In the Podlaskie, voivodship is 28%, and in the Łódzkie, voivodeship is 92%. Figure 1 presents data on electrified and non-electrified railway lines in Poland and the degree of electrification of railway lines in individual provinces.

Due to the varying degree of electrification of railway lines, the layout of passenger connections becomes problematic. In particular long-distance relationships, references are relatively often made using two locomotives. One of the vehicles equipped with a diesel drive pulls the train of passenger carriages on the non-electrified section. Then the electric

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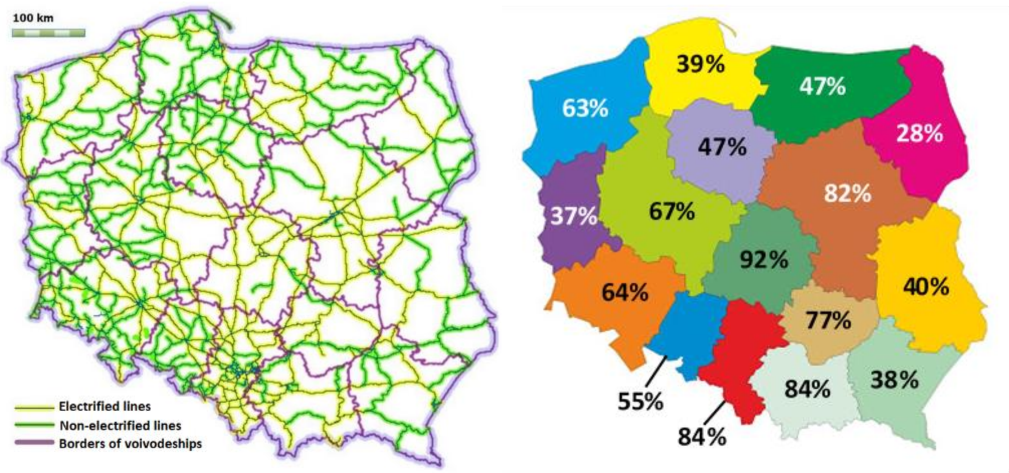

Fig. 1. Map of the railway lines in Poland, broken down by type of traction and share of electrified railway lines in individual voivodeships in Poland (sources: [3,4])

locomotive is changed at the station for further travel on the electrified line. This solution is demanding due to the need to engage two locomotives on one route. In addition, the mere time to switch locomotives extends the journey. For example, replacing locomotives on the "TLK Staszic" train from Szczecin-Lublin generates a 26-minute stop at the Piła Główna station [2].

The use of internal combustion vehicles in Poland is the domain of local carriers, where transport is carried out over relatively short distances. The largest Polish state-owned railway operator PKP Intercity (IC), which carries out long-distance connections, has mainly electric traction-powered rolling stock in its vehicle fleet. In the case of diesel rolling stock, in May 2022, PKP IC was equipped with 31 diesel locomotives, of which 27 were operated [5]. The most significant part (15 units) were locomotives of the SU42, SU4210, and SU4220 series, which are modernized versions of the SM42 shunting locomotives, where their production was terminated in 1993 [6].

The use of old vehicles, such as the modernized SU42 locomotives, not only affects the lower, compared to newer vehicles, maximum speed, which is 90 km/h [7]. The operation of this type of rolling stock is more likely to cause vehicle failures [8]. According to data for 2021, in 24.5% of the number of delays (111.2 thousand cases) in passenger rail transport, the reasons were related to the rolling stock. Most often assigned to the delay code 64-2, i.e., "Repair or replacement due to a breakdown (also using the help of other locomotives)" – 38.5 thousand cases generating 572 thousand min delays [9].

Due to a strictly planned timetable, any damage or occurrence of an undesirable event relating to railway vehicles [10, 11]. may affect other connections. In the worst case, it can also cause the train to be canceled. Based on the data from December 13, 2020, to April 7, 2021, in Poland [12], in 166 cases, a diesel traction PKP IC train was canceled. Instead, a replacement communication was launched, mainly by bus [13], where the generated costs were estimated at around 580,000 PLN [14].

For the above reasons, rail vehicles independent of electric traction in Poland are still necessary. Additionally, due to the significant age of many vehicles, investments in rolling stock are required [3]. Modernization and remotorization bring positive aspects, such as reducing fuel consumption [15]. It leads to a reduction of CO_2 emissions, which is a positive phenomenon with ambitious emission reduction plans [16]. However, the age of the vehicle remains significant. A solution entering the industry is using hydrogen to drive rail vehicles [17,18]. This solution is used for passenger transport in Western countries [19, 20]. However, it requires enormous financial outlays and developed infrastructure.

A good solution combining versatility and lower costs compared to hydrogen drives seems to be using multi-drive vehicles that can run on electrified and non-electrified lines [21, 22]. In this direction, activities are already underway in Poland, such as purchasing multiple dual-drive units [23] or announcing a tender by PKP IC to purchase dual-drive locomotives for passenger transport [24]. All this seems to be a promising strategy for solving problems related mainly to passenger transport.

The article has been divided into chapters by subject. The second chapter presents data on Poland's passenger rolling stock and rail transport. The design of the 111DE dual-drive locomotive, which could be used for passenger transport on all standard gauge lines, has been described in the third chapter [25]. The summary includes considerations about a solution that would enable using one locomotive on lines with electric traction and without. An explanation of why such a solution would eliminate the process of changing the locomotive, decrease travel time and improve the passenger transport quality in Poland has also been described.

2. Railway passenger transport in Poland

2.1. Railway passenger transport data in Poland

Rail passenger transport in Poland has been gaining more and more popularity in recent years. It is confirmed by data from the Office of Rail Transport (ORT) [26] for the period from January 2012 to May 2022 (Fig. 2). According to the data, the average monthly number of passengers for a given year from 2012 to 2019 increased from 22.8 million to 28 million passengers. However, due to the pandemic outbreak, there has been a considerable decrease in the number of passengers traveling by railway. After the announcement of the restrictions, the number of passengers fell to just 6.1 million in April 2020. It was the lowest value recorded in the ranking. From then on, with local downtime due to constraints, an increase in value is recorded. In the last recorded month, this value returned to the value from before the outbreak of the pandemic and has a chance to achieve the highest result in the summer months. The reason for this may be, among other things, the introduction by PKP IC of a program of discounts and amenities for traveling by railway in the summer [27], as well as running more trains [28]. An example of the profitability of introducing discount programs due to the popularization of railways is, among others, the German solution [28, 29] where a EUR 9 train ticket valid for three months was introduced.

The fluctuations for individual months are characteristic of the described index. The same applies to indicators such as operational performance, transport performance, and average travel distance of 1 passenger. Local factors influencing the indicators in rail transport include, among other things, the tendency of increased demand for long-distance transportation in the summer period. Increased average passenger distances and transport performance are recorded in these months. This is mainly related to holiday trips, where passengers travel long distances for vacation purposes, as opposed to other periods where passengers travel, for example, to work or school. Therefore, they do not cover significant distances due to the smaller distances between the place of residence and the destination.

In the case of all the indicators mentioned above, an upward trend has been visible since 2014, which was halted and significantly reduced by the pandemic outbreak. However, despite the worse period for rail carriers, based on the collected data, it can be noted that the return to the situation from before the COVID-19 virus emergence is happening [31]. Additionally, local factors, such as the summer period or the carrier's marketing campaigns, increase the demand for passenger rail transport. This means that the use of the rolling stock in these periods is the highest and requires appropriate maintenance and management.

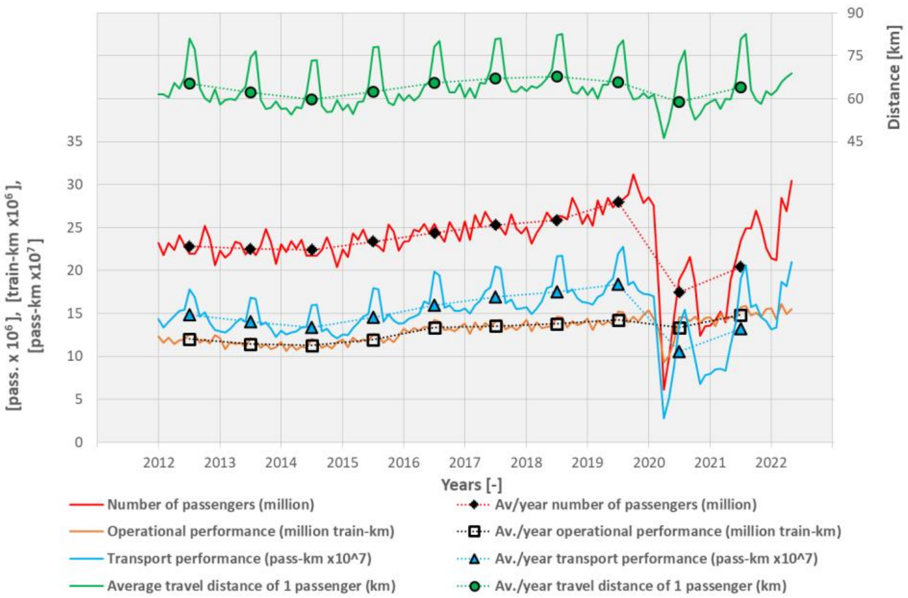

Fig. 2. Detailed monthly and annual average transport data for passenger railway transport in Poland over the years from I.2012 to V.2022 (source: own study based on the ORT's data [26])

2.2. Rolling stock

Traction vehicles

The growing demand for passenger rail transport is possible to cover thanks to an extensive fleet of rail vehicles. Figure 3 summarizes the number of passenger rail vehicles, considering the type and source of propulsion used by railway carriers in Poland in 2008-2021. Traction rolling stock can be divided into three main groups: Multiple Units, Locomotives, and Railcars. An additional criterion for the division is also the source of the drive.

For this reason, it is possible to divide vehicles into electric vehicles (which get electricity from the overhead line), diesel, and dual-drive. The most numerous group used for this type of transport are Electric Multiple Units (EMU). In 2021, there were 1,242 vehicles in Poland; the most significant number was recorded in 2015, i.e., 1,341. According to data from 2019 [32], this vehicle group was EMUs of the EN57 series or their modernizations and derivatives (726 units), which have been used in Poland since 1961. For this reason, the average age of EMU in the country in 2020 was 25.61 years [33]. Electric locomotives are the second largest group in passenger rail transport (342). The average age in 2020 was 33.19

years [33]. According to data from 2019 [32], the share of passenger electric locomotives with the maximum operating speed was as follows: up to 130 km/h - 74.4%, from 131 km/h to 160 km/h - 22.4%, from 161 km/h - 3.2%.

Regarding rail vehicles powered by diesel traction, the most numerous group are Diesel Multiple Unit (DMU) vehicles (246 units), which have doubled over the last 13 years. For Diesel locomotives, in 2021, the number of vehicles increased by 24 compared to the previous year to 129 units. However, this group of vehicles recorded the most significant decrease in quantity since 2008. Their number dropped from 341 number to 105 number in 2020, which means a more than threefold reduction in this type of rolling stock. The reason for a significant decrease in the number of diesel locomotives used for passenger transport may be measures and investments aimed at rejuvenating the vehicle fleet, as the average age of locomotives in 2020 was 43.38 years [33]. Among other things, due to age, in 2019, only 10.2% of vehicles of this type had a maximum operational speed from 131 km/h to 160 km/h. The remaining vehicles belonged to the group with a maximum operating speed lower than 130 km/h (89.8%) [32].

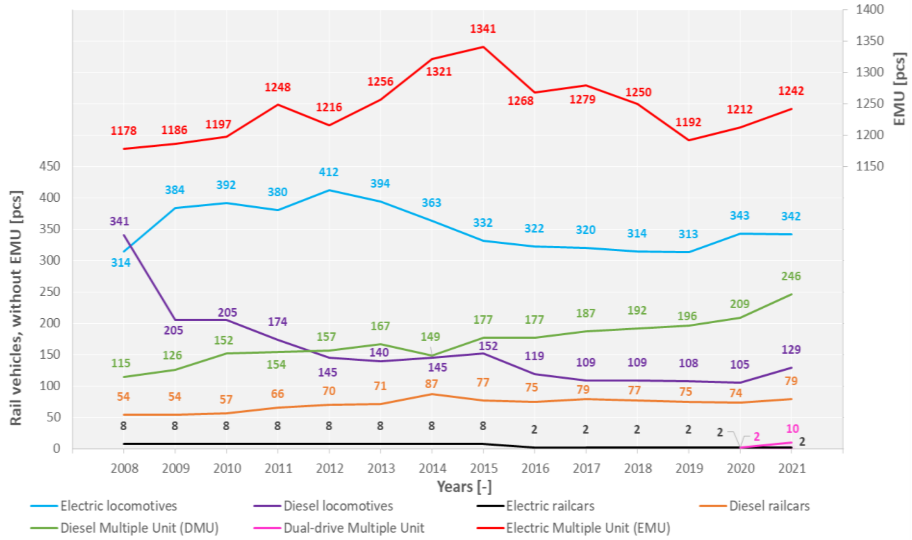

Fig. 3. Number of rolling stock divided into types of drive used for passenger transport in Poland in years: 2008 – 2021 (source: own study based on the ORT's data [34])

The least numerous rail passenger traction vehicles in Poland are railcars, of which 81 in 2021 were in total, including 79 diesel-powered and two electric. The average age of vehicles in 2020 was 17.01 years for diesel railcars and 15 years for electric railcars, respectively. All such vehicles are designed for a maximum operating speed of 130 km/h.

In the case of the newest vehicle type in the list, i.e., the Dual-drive Multiple Unit, in Poland, it appeared on the equipment of passenger carriers in 2020 in the number of 2 units, according to ORT data [35]. In 2021, the number of these units increased to 10. These two-drive multiple units have two types of drive: combustion and electric traction. This solution allows the vehicle to move on electrified and non-electrified lines, significantly increasing its versatility and travel possibilities on any railway line. These units were manufactured by the Polish company Newag [36]. Local carriers ordered Hybrid Multiple Units IMPULS 2 type 36WEh and Marshal's Offices, such as Koleje Dolnośląskie (64%) [23], Marshal's Office of the West Pomeranian Voivodeship (63%) [37], Marshal's Office of the

Podkarpackie Voivodeship (38%) [38] (% - the degree of electrification of the railway line in the voivodeship).

The answer to the market requirements is also the Polish dual-drive vehicle built by FPS Cegielski and designed by the Łukasiewicz Research Network - Poznan Institute of Technology, Center of Rail Vehicles [22]. The railcar, designed in two versions, i.e., two or three sections, called PLUS, is a vehicle that can move both using electric and diesel traction. The "Light rail bus for regional traffic" project is in the final implementation stage. The vehicle is currently being put into operation, which means that more dual-drive passenger vehicles may soon appear on railway tracks. Dual-drive locomotives intended for passenger transport in Poland have not yet been used for this purpose.

Carriages

The leading group of traction vehicles used in passenger rail transport in Poland is Multiple Units, of which there were 1,498 units in 2021. Multiple units have many advantages; however, it may be problematic to adapt the appropriate size of vehicle sets (e.g., connecting traction vehicles) to the flow of passengers on a given line. Trains consisting of a locomotive-pulling wagon are characterized by greater flexibility in terms of the selection of the transport quantity of passengers. In Poland, in 2021, passenger carriers were equipped with 471 locomotives, and the number of carriages intended for passenger transport was 2,238. The largest group was vehicles with seats (1,951) [34]. Figure 4 shows the number of carriages of passenger carriers in 2011-2021.

In the case of the most numerous group of this type of vehicle, there has been a significant decrease since the beginning of the ranking, where since 2011 (3089 units), the number of vehicles has been reduced by 37%. The smallest number of vehicles was recorded in 2019 (1920). Since then, this number has been increasing every year. The number of remaining wagons in 2021 was much smaller compared to vehicles with seats and was as follows: Sleeper (133), Catering (82), Couchette (57), and Luggage (15). According to data for 2020, the average age of passenger carriage vehicles in Poland was estimated at 31.59 years [33].

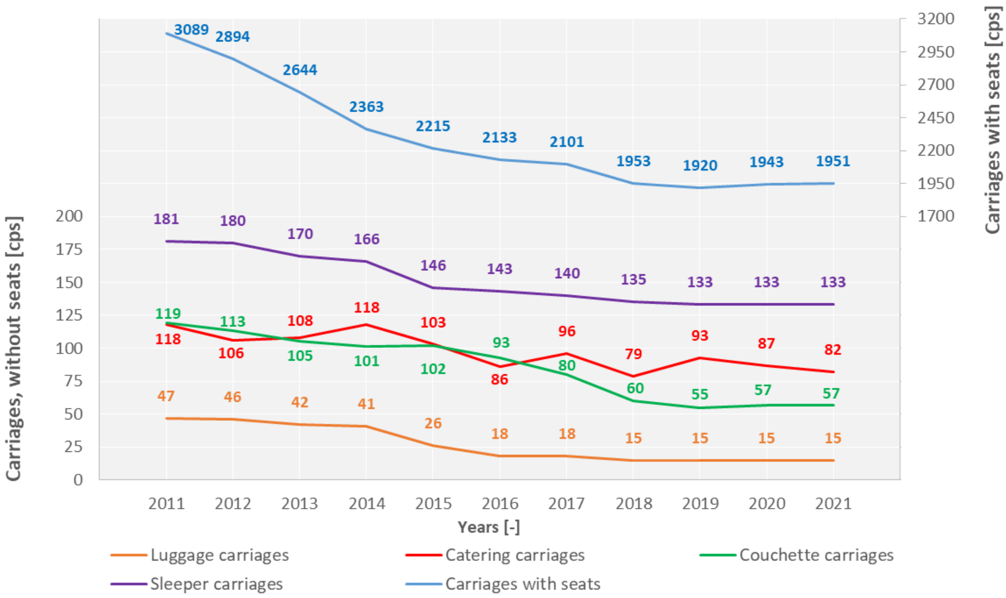

Fig. 4. Number of railway carriages used for passenger transport in Poland in years: 2011 – 2021 (source: own study based on the ORT's data [34])

The maximum operating speed of passenger trailers with seats was up to 130 km/h - 11.8%, from 131 km/h to 160 km/h - 79.6%, and above 161 km/h - 8.6%. In the case of Sleeper carriages and couchette carriages, 5.9% of vehicles were adapted to the maximum operating speed above 161 km/h; the remaining share were vehicles with the described index ranging from 131 km/h to 160 km/h [32].

Rail vehicles equipment

Passenger rolling stock in Poland is characterized by considerable diversity. Various types of rolling stock are used, and the average age of vehicles of a particular kind often exceeds 30 years. It means that some vehicles were built at a time when various amenities such as Passenger Information System (PIS) or Air Conditioning (A/C) were not standard. Along with the development of railways, increasing the accessibility of rail transport, and the convenience of use, passenger-friendly solutions were used, which are considered standard today. An example is the adaptation of a vehicle for the transport of Persons with Reduced Mobility (PRM). Actions encouraging passengers to use the railways, such as the modernization or rejuvenation of the rolling stock, are undoubtedly beneficial in popularizing this type of transport. Table 1 presents the equipment of passenger railway vehicles in Poland.

Table 1. Equipment of rail vehicles used for passenger rail transport in Poland in 2020. Where: E – Electric, D – Diesel (source: own study based on the ORT's data [33, 35])

												
Type of rolling stock	**Locomotives**		**Multiple Units**			**Railcars**		**Carriages**				
	E	**D**	**E (EMU)**	**D (DMU)**	**Dual-drive**	**E**	**D**	**With seats**	**Lug-gage**	**Cate-ring**	**Couche-tte**	**Sleeper**
Number of vehicles	**343**	**105**	**1212**	**206**	**5**	**2**	**74**	**1923**	**15**	**87**	**57**	**133**
A/C	285	76	785	168	5	2	64	935	0	77	23	24
Heating	285	70	1211	205	5	2	74	1923	15	87	57	133
Access to WiFi	0	0	535	106	2	2	34	437	0	38	11	8
Electric sockets for passengers	0	0	526	81	5	0	7	787	0	5	23	20
Cell signal amplifier	0	0	324	39	3	0	11	403	0	20	3	6
Closed circuit toilet	2	0	788	190	5	2	60	1208	0	77	23	82
GPS location	273	1	867	167	5	2	55	438	0	25	0	0
Places for bicycles	0	0	1178	196	5	2	72	207	15	2	0	0
Changing table for babies	0	0	840	142	5	2	28	80	0	0	10	20
Ticket machine	0	0	396	59	0	2	7	0	0	0	0	0
Electronic PIS	18	0	1147	195	5	2	68	795	0	47	1	42
Braille markings	0	0	336	26	5	0	0	349	0	10	0	0
Places for PRM	0	0	924	104	5	0	69	96	0	0	10	14
Frontal cameras	225	36	876	152	5	2	51	59	0	0	0	0
Interior monitoring system	13	0	892	145	5	2	57	80	0	2	0	0

3. Dual-drive locomotive 111DE

The 111DE dual-drive locomotive is the answer to the need to operate both electrified and non-electrified lines. It was created under the Intelligent Development Operational Program nr POIR. 01.02.00-00.0191/16-00 "A locomotive platform with advanced diesel-electric (multi-system) drive systems". The National Centre for Research and Development co-financed the project. Its contractors are Pojazdy Szynowe PESA Bydgoszcz SA and Łukasiewicz Research Network - Poznan Institute of Technology, Center of Rail Vehicles, formerly Łukasiewicz Research Network - Rail Vehicles Institute "TABOR" in Poznań.

The vehicle type 111DE is a four-axle standard-gauge universal locomotive with a maximum power of 2,800 kW powered by electric traction or about 2,000 kW powered by a diesel generator. Project assumptions:

- two power sources: from the traction network or a diesel generator with a voltage of 3 kV DC,
- maximum power: 2,800 kW (electric traction drive),
- combustion engine power: approx. 2000 kW,
- structural weight of the locomotive: 86 t / 4 axles,
- modular structure of the locomotive,
- use in passenger and intermodal cargo traffic and for shunting works in the area of reloading terminals
- compliance with the technical specifications of the interoperability of the rail system in the European Union (TSI)

Between the driver's cabins is a machinery compartment consisting of an electric section, a pneumatic section, and a generator section. The individual subassemblies have been arranged in such a way as to evenly distribute their weight on the stand and thus achieve an even pressure of the wheelsets on the rails. The generator is driven by a Cummins QSK60 turbocharged diesel engine with a power of 2013 kW. It is a liquid-cooled 16-cylinder V unit. The engine speed range is 700 - 1800 rpm. In addition, the engine is equipped with an EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reduction) exhaust gas after-treatment system that meets the requirements of Directive 97/68/EC of the European Parliament and of the Council, stage III B (cycle F).

The Hitzinger SGE 090B 06T synchronous generator with a capacity of 2440kVA was used as a traction generator. The electric drive is provided by four asynchronous motors powered by traction converters. Electric energy from the traction through a pantograph feeds through the main switch to the line filter and then to the traction converters. The locomotive can be electrodynamically or resistively braked. The generator voltage after the rectifier is 3 kV DC. In the electrical compartment, there is a converter to power the auxiliary network of the vehicle 3x400V, 50 Hz. The accumulator batteries and the control, lighting, communication signaling, registration, and railway traffic safety circuits are powered with a safe voltage of 24V DC. 230V voltage is used to supply other auxiliary devices. The equipment layout on the 111DE locomotive is shown in Figure 5, and technical data are in Table 2.

The theoretical traction characteristics of the locomotive 111DE (Fig. 6) with passenger carriages weighing 600 tons powered by electric traction show that realizing the power of 2800kW, it can run on a flat track at a speed of 160 km/h. On slopes with a gradient of 7‰, the locomotive's speed under electric traction is less than 120 km/h. A locomotive with a set of passenger carriages weighing 600 tons, powered by a power generator with a power of 1139 kW, can run on a flat track at a speed of 115 km/h while on a track with a 7 ‰ gradient, the speed is 65 km/h.

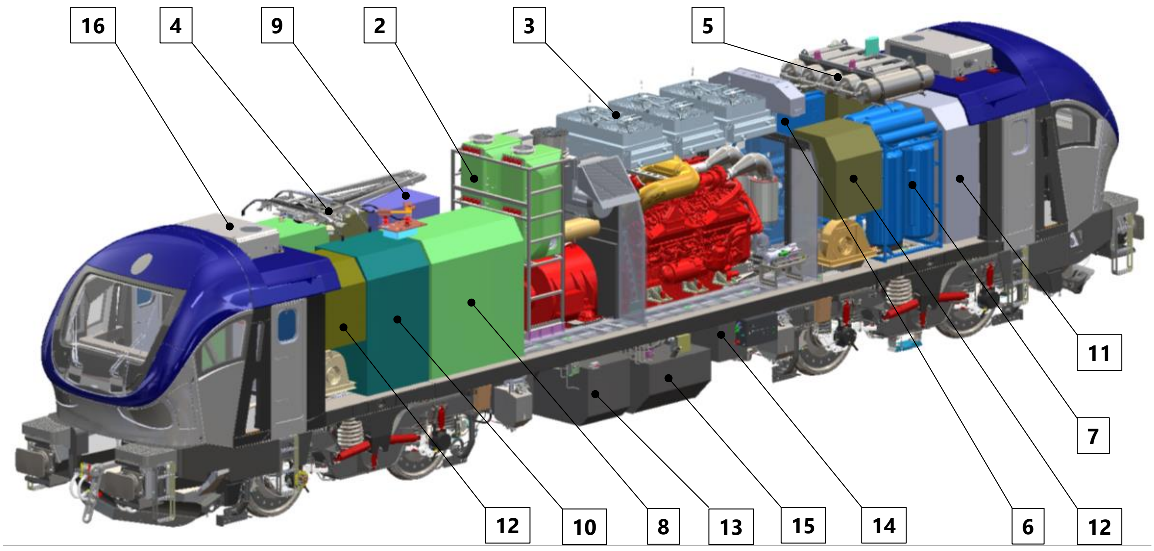

Fig. 5. Layout of equipment on the 111DE locomotive. Labels: 1- power generator, 2- a set of SCR catalytic systems, 3- a combustion engine cooling unit, 4- a pantograph, 5-main air tanks, 6- compressor module, 7- board module, 8- power inverters cabinet, 9- cooling column with braking resistor, 10- HV cabinet, 11- ETCS cabinet, 12- LV cabinet with electric motors ventilator, 13- line choke, 14- battery box, 15- fuel tank, 16- air conditioning unit (source: [21])

Table 2. Technical data (source: [25])

Parameter	Electric drive	Combustion drive
Voltage	3 kV DC traction network	3 kV DC diesel generator
Max. Power	2 800 kW	1 560 kW
Combustion engine power	-	2 030 kW
Electrodynamic brake power	1 000 kW	
Type of transmission	Electric DC-AC	Electric AC-DC-AC
Max. tractive force	300 kN	
Max. Velocity	160 km/h	
Axle arrangement	Bo'Bo'	
Track gauge	1 435 mm	
Loading gauge	PN-EN 15273-2 G1	
Vehicle length	19 750 mm	
Distance between the axles of the bogies	10 700 mm	
Bogie base	2 800 mm	
Wheel diameter	1 250 mm – new 1 170 mm – used	
Max. total weight	86 t	
Safety systems	SIFA, SHP, RS, ERTMS/ETCS	
Multiple tractions	for up to 2 vehicles	

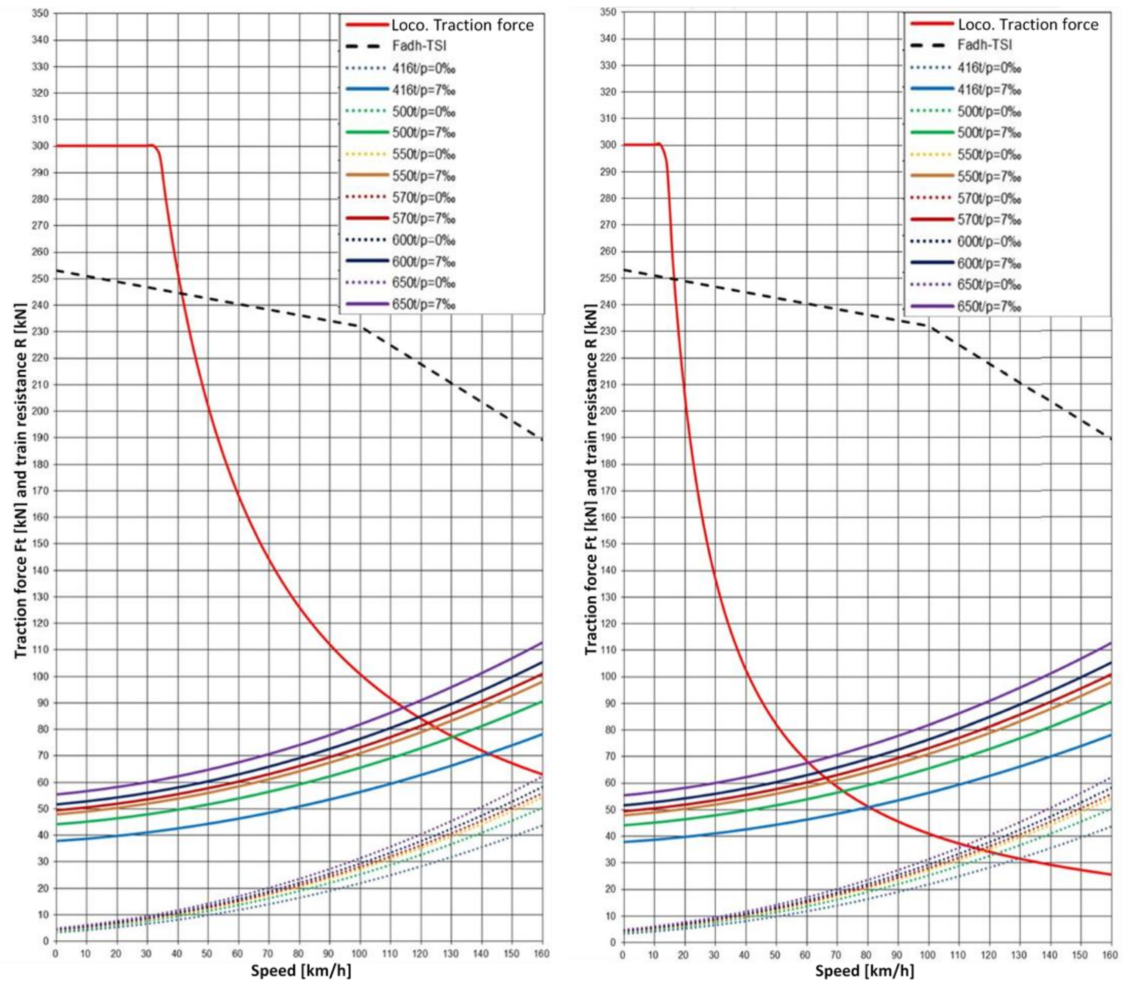

Fig. 6. Theoretical traction characteristics of the 111DE locomotive. Left: electric traction (mechanical power on the circumference of the driving wheels 2800 kW) and curves of resistance to motion for passenger trains (wagon train 416 ÷ 650 t + locomotive. On the right: diesel traction, passenger traffic (power supply for the wagons 565 kW) (mechanical power on the circumference of the driving wheels 1139 kW), and resistance curves for passenger trains (wagon train 416 ÷ 650 t + locomotive). (source: own data)

4. Summary

Considering the scale of railway use in Poland and its continuous development, the use of dual-drive vehicles by passenger carriers is becoming increasingly popular. In Poland, 37% of railway lines can only be operated by vehicles with a driven independent of electric traction, which, when handling mixed railway connections (non and electrified lines), generates logistical and operational problems for railway carriers. Mainly for this reason, the use of dual-drive vehicles brings many benefits.

The advantages of using the 111DE locomotive for passenger transport are manifold. Traction characteristics confirm that the described dual-drive locomotive can be successfully used in passenger transport because it provides sufficient operational indicators. The most significant advantage is running the train on an electrified route without electric traction.

The time saved when changing locomotives with different propulsion can significantly shorten the journey and minimize the risk of delays due to shunting works.

The reliability of the 111DE locomotive, since it has two types of drive, is also greater than that of conventional locomotives. In the event of a breakdown on the electrified route, it is possible to bring the train to its destination using a combustion generator. The vehicle can continue to run successfully even in an overhead line failure. Additionally, shunting works can be performed without the use of other shunting locomotives. Thanks to all these advantages, passenger transport carried out by the 111DE locomotive can be improved, and the risk of delays can be significantly reduced. The operating costs of servicing a mixed route, i.e., with and without electric traction, with one dual-drive locomotive, will also be lower than that of servicing the same section with two different vehicles.

The downside of using a dual-drive locomotive in passenger transport is the higher cost of purchase and operation compared to conventional vehicles, which may not be profitable for smaller carriers. However, considering the intended use of such a locomotive, i.e., medium and long-distance transport to operate a mixed route, it seems reasonable for carriers offering passenger transport throughout Poland to have a fleet of dual-drive locomotives.

Implementing this locomotive type for use on railway lines in passenger transport, despite the increased purchase costs compared to conventional vehicles, may be associated with many time and economic benefits during operation. For this reason, considerations regarding these aspects may become the subject of future work.

Nomenclature

A/C – Air Conditioning
PIS – Passenger Information System
PRM – Persons with Reduced Mobility
EGR – Exhaust Gas Recirculation
EMU – Electric Multiple Unit
DMU – Diesel Multiple Unit
DD – Double-decker
IC – Intercity
ORT – Office of Rail Transport
SCR – Selective Catalytic Reduction

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