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Effectiveness evaluation of a high-power diesel locomotive using a twin-engine propulsion system

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One of the methods of reducing the operating costs of high-power diesel locomotives, and especially the costs of fuel consumption, is the use of a drive system with two engines. The paper presents the characteristics of selected designs of multi-engine locomotives used in Poland and around the world and assesses the efficiency of a high-power six-axle locomotive in two variants of the drive system configuration: single and double-engine using a main engine with a power of 3000 kW and an auxiliary engine with a power of 400 kW. The comparative analysis took into account: the costs of maintaining the drive system, fuel consumption costs, AdBlue consumption costs and environmental costs. The analyses carried out showed that the double-engine variant ensures compliance with the exhaust emission requirements according to the Stage V standard as well as optimal adaptation of the locomotive to operation with a significant share of idle time.

Key words: *multi-engine locomotives, diesel traction efficiency, emission in rail transport, LCC assessment*

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1. Introduction and literature analysis

With the growing demands for climate protection and the need to increase energy efficiency, rail transportation plays a crucial role in the European Union's sustainable development strategy. Particular attention is paid to the need to reduce the operating costs of internal combustion traction vehicles and bring them into compliance with current emission standards [14]. The literature emphasizes the importance of field studies on the actual emissions of pollutants generated by rail vehicles [16, 24], as well as the need to implement technical solutions, such as engine or injection system modifications [17, 19]. As stated in the paper [14], decarbonizing the rail sector requires both technological and systemic changes. A more holistic approach is proposed by Fonseca-Soares and co-authors [9], highlighting the need to incorporate Life Cycle Analysis and integrate rail with other forms of transportation, among other considerations, into emissions analyses.

In parallel, measures are being developed to enhance energy efficiency and reduce locomotive operating costs. The modernization of older types of vehicles, such as the SM42-series locomotives, significantly reduces fuel consumption, as confirmed in studies [26]. Similar conclusions are presented by Andrzejewski et al. in [1], highlighting the crucial importance of fuel consumption and drive train energy intensity in the operational evaluation of different locomotive types.

In the context of power supply system development, the forecasts presented in [12] suggest that despite the intensification of electrification processes in the rail network, the demand for liquid fuels in the rail sector will remain high at least until 2040, especially in sections without electric traction. In response to these challenges, new design solutions are emerging, including vehicles with hybrid drivetrain that combine internal combustion with battery-powered electric propulsion. As the authors [3] point out, the use of this type of locomotive, tested in real-world conditions, brings tangible benefits in terms of reduced fuel consumption and lower emissions.

CO_2 regulations are also becoming increasingly important. As described in more detail in Section 2 of the paper, EU Regulation 2016/1628 establishing Stage V emission standards [7], Directive 97/68/EC [4], and the tenets of the EU's "Fit for 55" package [8] remain the key documents in this regard. A very valuable review of current legal and technical requirements in the context of propulsion systems was made by the authors of the publication [18]. Conclusions from previous studies indicate the need to implement modern design solutions in diesel rolling stock, in line with current environmental and operational requirements. One such solution is the use of multi-engine propulsion systems, which allow for the optimization of engine operation depending on the operating conditions, such as idling or tractive operation [20, 28].

The paper presents a comparative evaluation of the efficiency of a high-power diesel locomotive in two variants of the drivetrain configuration: single-engine and twin-engine, utilizing a 3000 kW main engine and a 400 kW auxiliary engine.

2. Environmental emission requirements for diesel locomotives

The emission standards applicable to new and retrofitted diesel locomotives align with the European Commission's current policy, as outlined in the European Union's Green Deal [6]. It outlines goals for the European Union to address climate and environmental problems. The formulated goals refer to a resource-efficient and competitive economy that aims to achieve zero greenhouse gas emissions by 2050. European emission standards for non-road vehicles were first announced in 1997 and implemented in two stages: Stage I in 1999 and Stage II between 2001 and 2004. Stage I/II standards did not cover engines used in railroad locomotives. It was not until the introduction of Stage IIIA and IIIB standards between 2006 and 2013 that strict limits were introduced for locomotive engines. The Stage IV emissions standard was introduced in 2014 and applies to two categories of engines, ranging from 56 kW to 560 kW. Compliance with this standard requires the use of exhaust after-treatment systems, such as selective catalytic reduction (SCR) or diesel particulate filter (DPF). Stage V, the latest emissions standard, covers RLL engines used in locomotives and RLR engines in railroad cars. The standards take effect in 2019 for engines with a power rating below 56 kW and above 130 kW, and in 2020 for engines with a power rating between 56 kW and 130 kW [25].

Regarding national requirements, Poland has a Decree of the Minister of Economy dated April 30, 2014, which outlines detailed requirements for the emission of gaseous and particulate pollutants by internal combustion engines, including those used in railroad vehicles [22]. The regulation implements selected provisions of EU law into the national legal order and includes, among other things, emission limits for specific engine categories.

Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements for emission limits for gaseous and particulate pollutants and type approval for internal combustion engines intended for non-road mobile machinery, amending Regulations (EU) No. 1024/2012 and (EU) No. 167/2013 and amending and repealing Directive 97/68/EC (OJ. EU. L 252/53, 16.9.2016) as amended by Regulation (EU) 2022/992, regulating the requirements for permissible toxic components contained in exhaust gases, is currently in force for railroad vehicles in Europe. Article 4 of Regulation 2016/1628 divides engines into categories, of which the RLL category includes engines for use exclusively in, for propulsion of, or intended for propulsion of locomotives. According to Article 4, Section 1, point 7 of Regulation 2016/1628, the RLL category for engines used for propulsion in locomotives is defined in two subcategories (Table 1).

Table 1. Subcategories of the RLL category railroad engines [7]

Category	Ignition type	Speed operation	Power range [kW]	Subcategory	Reference power
RLL	all	variable	P > 0	RLL-v-1	Maximum net engine
		constant	P > 0	RLL-c-1	Rated net power

Regulation 2016/1628 introduced Stage V, which has stringent limits for the content of particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) in the exhaust gases. Stage V introduced a new particulate number emission limit, PN, which requires particulate filters on all engine types. Before that, there had been harmonization of EU regulations with US Tier standards. However, harmonization was largely lost at Stage V.

Table 2. Stage V emission limits for RLL category engines [7]

Engine sub-category	Power range [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	A
RLL-c-1 RLL-v-1	P > 0	3.50	(HC + NO_x ≤ 4.00)		0.025	6.00

Stage V emission limits for RLL category railroad engines as defined in Article 4, Section. 1, point 7 of Regulation 2016/1628 is shown in Table 2.

3. Examples of solutions for multi-engine systems in locomotives

Multi-engine locomotives are railroad vehicles equipped with multiple drive units that can be started and stopped as needed to meet current traction requirements. With this design, higher operational flexibility is achieved, along with optimized fuel consumption and reduced emissions. Multi-engine locomotives offer several significant operational and environmental advantages over traditional designs with a single large diesel engine. The most important advantages of such solutions include:

a) Possibility of working at partial power

Locomotives equipped with several drive units allow flexible management of available power. In the case of smaller loads, for example, during shunting, driving with light formations, or during prolonged stops, the operation of all engines is not required. In such situations, it is possible to turn off some units and leave only the necessary units active. This approach reduces fuel consumption and unnecessary wear and tear on mechanical components, resulting in greater durability and increased overall operating efficiency of the locomotive.

b) Optimization of fuel consumption

Adapting the number of running units to actual traction demand enables a significant reduction in average fuel consumption. In traditional locomotives, the large internal combustion engine often operates in a suboptimal load range, resulting in increased fuel burn. In multi-aggregate designs, each engine can operate closer to its optimum characteristics, and it is possible to quickly start additional drive units if necessary.

c) Reduction of CO_2 and NO_x emissions

Reduced fuel consumption directly translates into reduced carbon dioxide (CO_2) emissions, the main greenhouse gas responsible for climate change. In addition, emissions of nitrogen oxides (NO_x) and particulate matter (PM) are also reduced, thanks to the use of modern aggregates that meet current emission standards (such as EPA Tier 4 or Stage V). This aspect is particularly important in the context of tightening environmental regulations in the rail transportation sector.

d) Higher reliability

Multi-engine locomotives are characterized by greater resistance to failure compared to single-engine designs. In the event of damage or failure of one unit, the remaining units can continue operating, allowing them to complete manoeuvres or reach the nearest service station. Such a solution increases the operational reliability of the locomotive and minimizes the risk of downtime in railroad traffic [11].

To illustrate the variety of existing solutions for multi-engine systems, the following table summarizes selected types of multi-engine locomotives, along with their basic technical information and performance characteristics.

Table 3. Examples of multi-engine locomotives [13, 15, 27, 29]

Locomotive type	 **Traxx DE ME**	 **6Dk**	 **6Dl (SU4210 series)**	 **Class Dr19**
Manufacturer	Bombardier	PESA	NEWAG	STADLER
Year of manufacturing	2013	2014	2013	2023
Engine configuration	4 × Caterpillar C18	2 × Caterpillar C15	2 × Caterpillar C18	2 × Caterpillar C32
Total power	4 × 563 kW (2252 kW)	2 × 403 kW (806 kW)	2 × 563 kW (1126 kW)	2 × 950 kW (1900 kW)
Maximum speed	160 km/h	80 km/h	95 km/h	120 km/h
Scope of application	Passenger and freight trains	Shunting work, light freight	Freight trains and shunting work	Freight trains and shunting work

4. Characteristics of the analyzed variants of propulsion systems

In this paper, two variants of a high-powered diesel locomotive's drive train are analyzed in a comparative study:

1. Single-engine standard propulsion system with Caterpillar Type C175 3000 kW, Stage V engine
2. A twin-engine propulsion system using a 3000 kW C175 main engine and a 430 kW Caterpillar C13B auxiliary engine, Stage V. The auxiliary engine acts as a power unit to support the locomotive when stationary at stations and passing stations, and performing loose shunting work.

Table 4. Summary of the basic parameters of the engines in the analyzed drive systems

Specification	Main engine	Auxiliary engine
Manufacturer	Caterpillar	Caterpillar
Type:	C175	C13B
Power:	3000 kW	430 kW
Torque	16852 Nm	2648 Nm
Capacity:	85.7 dm^3	12.5 dm^3
Exhaust emission standard	Stage V	Stage V
Cylinder arrangement	V16	R6
Rotational speed	1800 rpm	1800 rpm
Exhaust gas treatment module	SCR technology, AdBlue	AdBlue

a)

Fig. 1. CAT C175-16 engine with 3000 kW [5]

b)

Fig 2. CAT C13B engine with 430 kW [10]

The C175 type main engine is a popular drive unit in modern high-powered diesel locomotives. The engine is used, among other applications, in the EURO 4001 series of locomotives featuring the Co'Co' axle system, offered by Stadler, for both freight and passenger services at speeds of up to 160 km/h. The engine meets the latest emission regulations (EU Stage V). In addition, they are adapted to the use of HVO fuel, supporting the decarbonization of the transportation sector. EURO 4001 locomotives are operated in freight transport in France by Captrain France, among others, as well as by carriers outside Europe (South America, New Zealand).

5. Efficiency evaluation of the single- and twin-engine variants

5.1. Performance and cost analysis of propulsion system variants under different operating scenarios

Based on the actual costs of diesel fuel, AdBlue solution, and maintenance and repair costs for internal combustion engines, an evaluation of the efficiency of the single- and twin-engine variants of the propulsion system configuration was conducted. The comparative analysis included:

– the cost of maintaining the propulsion system
– fuel consumption costs
– AdBlue consumption costs
– environmental costs.

The comparative analysis of the propulsion system includes a comparison of a single-engine variant with a Caterpillar Type C175 engine with a twin-engine variant that uses a Caterpillar Type C175 primary engine and a Caterpillar Type C13B auxiliary engine. In the analysis for the twin-engine variant, three operating scenarios were considered, which differ in the share of main engine C175 and auxiliary engine C13B operating time in total locomotive operating time:

1. Scenario 1: 60% of the work is done by the C13B engine and 40% by the C175 engine
2. Scenario 2: 50% of the work is done by the C13B engine and 50% by the C175 engine
3. Scenario 3: 40% of the work is done by the C13B engine and 60% by the C175 engine.

5.2. Maintenance cost comparison

The measure of the interval for performing inspections and periodic repairs of internal combustion engines is the actual operating time expressed in engine hours. Reducing the operating time of the main engine of the C175 by eliminating idling has a significant impact on extending the duration of periodic engine maintenance and repairs.

The calculations take into account the locomotive's actual operating profile at the rail carrier, which varies depending on the engine load. In addition, the following assumptions were made:

- engine load at locomotive idling within 300–400 kW
- the engine obtains power (except for idling) at 1800 rpm
- average operating time of the locomotive: 6400 [hours/year]
- the operating time of the engine: 32,000 hours.

The analysis of engine maintenance costs included material and labor costs. The analysis required obtaining source data from Caterpillar Inc., the internal combustion engine manufacturer, regarding the detailed scope of activities resulting from the maintenance plan for the C13B auxiliary engine and the C175 main engine, from 500 hours to 12,000 hours. Due to the confidentiality of the data provided, unit cost information for individual inspections and repairs is not included in this paper.

A comparison of total maintenance costs and unit costs for the single-engine variant with a Caterpillar type C175 engine and the twin-engine variant (C175 + C13B) for all three operating scenarios considered is shown in Table 5 and Fig. 3. The analysis covered an operating time of 32,000 hours (approximately 5 years), and the interval for primary repair of the C175 engine was assumed to be extended to 24,000 hours, as per the manufacturer’s instructions.

Table 5. Comparison of maintenance costs of the single-engine variant (CAT C175) and the twin-engine variant (C175 + C13B) for three operating scenarios

Specification	Single-engine variant	Two-engine variant Scenario 1	Two-engine variant Scenario 2	Two-engine variant Scenario 3
Total cost of engine maintenance (thous. PLN)	3,700.9	1,136.1	1,399.1	3,133.6
Unit cost of engine maintenance (PLN/hour)	115.7	35.5	43.7	97.9

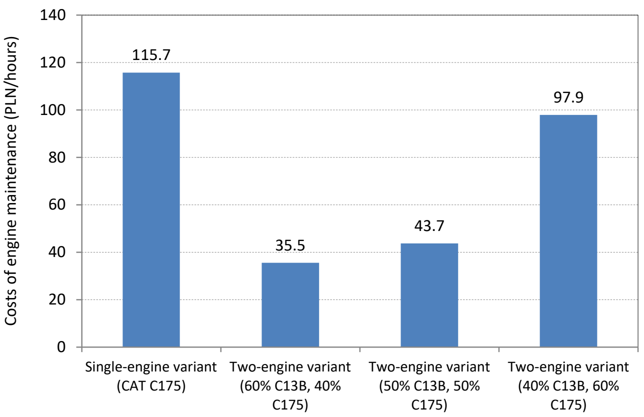

Fig 3. Comparison of unit costs of engine maintenance (PLN/hours) for the single-engine variant (CAT C175) and the two-engine variant (C13B and C175 engine) for three operating scenarios

The analysis shows that for the twin-engine variant, reducing the idling time of the C175 main engine can result in unit costs [PLN/hour] being reduced by as much as 69.3% compared to 15.4%. Annual savings range from PLN 113,920.00 to PLN 513,280.00 over a period of 32,000 hours of locomotive operation (5 years of operation).

5.3. Comparison of fuel consumption costs

Figures 4 and 5 show graphs of power (in kW) and fuel consumption (in g/kWh) for CAT C175 and CAT C13B engines. The charts indicate a power range of 300–400 kW, which corresponds to the locomotive's idle power requirements. From Figure 4, it can be observed that within this range, the C13B engine operates within the optimal range of specific fuel consumption characteristics: 199.3–200.6 g/kWh, in contrast to the C175 engine, for which consumption ranges from 240.7 to 245.2 g/kWh.

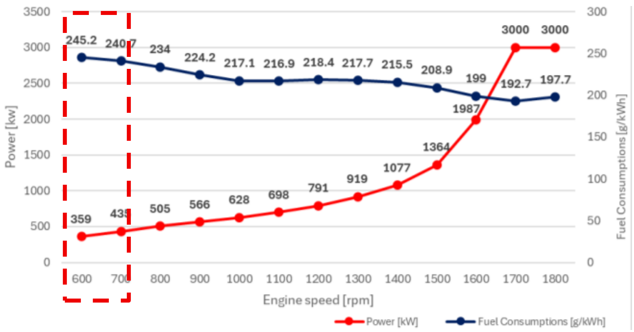

Fig. 4. Power and specific fuel consumption of the CAT C175 3000 kW engine as a function of speed

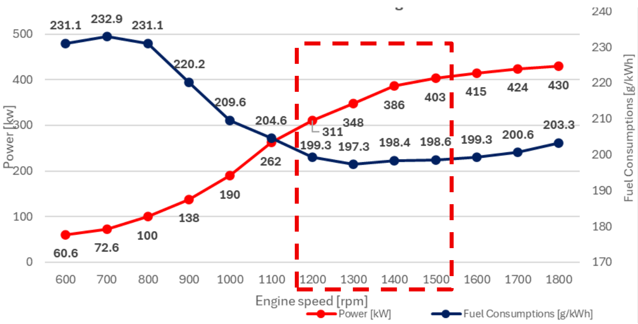

Fig. 5. Power and specific fuel consumption of the CAT C13B 430 kW engine as a function of speed

Tables 6 and 7 summarize the detailed calculations for the single- and two-engine variants, comparing idle fuel consumption. The calculations took into account the locomotive's actual operating profile at the carrier and:

- the required engine load when the locomotive is idling: 300–400 kW
- average operating time of the locomotive: 6400 [hours/year]
- the cost of diesel fuel: PLN 4.90 net/liter.

The analysis was conducted for three operating scenarios, which differ in the proportion of locomotive idling time to total operating time: 40%, 50%, and 60%.

Table 6. Consumption costs of fuel at idle in a single-engine variant (C175 engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
Average fuel consumption at idle [dm^3/hr]	113.5	113.5	113.5
Average fuel consumption at idle [dm^3/year]	435,648.0	363,040.0	290,432.0
Fuel cost [thous. PLN/year]	2134.7	1778.9	1423.1

Table 7. Fuel consumption costs at idle in the two-aggregate variant (C175 engine + C13B engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
Average fuel consumption at idle [dm^3/hr]	93.8	93.8	93.8
Average fuel consumption at idle [dm^3/year]	360,192.0	300,160.0	240,128.0
Fuel cost [thous. PLN/year]	1764.9	1470.8	1176.6

The analysis shows that the fuel consumption of the two-aggregate variant, in which only the auxiliary engine C13B runs at idle with a power demand of 400 kW, can be reduced by 17.3%. During train operation, a high-powered basic unit (CAT C175) is used, and fuel consumption for both variants is identical.

Figure 6 shows a comparison of idling fuel consumption costs for a single-engine variant (CAT C175) and a two-engine variant (CAT C13B and C175) as a function of idling time. In the two-aggregate variant, thanks to the reduction of the C175 main engine's operating time, the savings range from PLN 246,489.60 to PLN 369,734.40 in one year of locomotive operation.

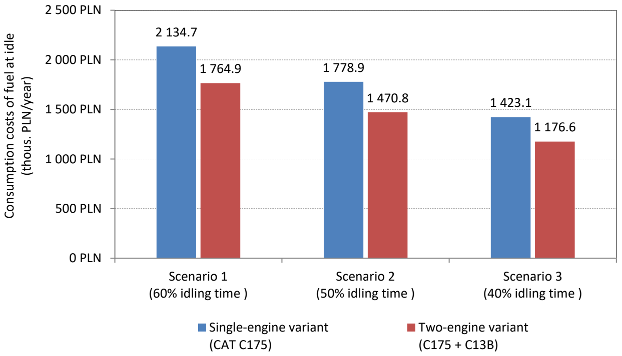

Fig. 6. Comparison of annual fuel consumption costs at idle for single-engine and two-engine variants depending on the operating scenario

5.4. Cost comparison of AdBlue consumption

The consumption of AdBlue solution is directly proportional to diesel fuel consumption, and, according to the manufacturer's declaration, it ranges from 3% to 8%, depending on the type of engine [2, 21]. The use of two engines not only reduces fuel consumption at idle but also significantly reduces the frequency of hydrocarbon neutralization in the exhaust gas aftertreatment system of the C175 engine, as it does not operate under low loads. According to the manufacturer, the C175 engine's AdBlue urea consumption accounts for 7.8% of the fuel consumption.

Tables 8 and 9 summarize the detailed calculations for the single- and two-engine variants, comparing AdBlue consumption. The calculations took into account the actual operating profile of the locomotive and the cost of AdBlue at a net price of PLN 2.25 per liter. The analysis was conducted for three assumed operating scenarios.

Table 8. Costs of AdBlue consumption at idle in a single-engine variant (C175 engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
Average fuel consumption at idle [dm^3/year]	435,648.0	363,040.0	290,432.0
Average AdBlue consumption [dm^3/year]	33,980.54	28,317.12	22,653.70
AdBlue cost [PLN/year]	76,456.22	63,713.52	50,970.82

Table 9. Costs of AdBlue consumption at idle in the two-aggregate variant (C175 engine + C13B engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
Average fuel consumption at idle [dm^3/year]	360,192.0	300,160.0	240,128.0
Average AdBlue consumption [dm^3/year]	28,094.98	23,412.48	18,729.98
AdBlue cost [PLN/year]	63,213.70	52,678.08	42,142.46

Figure 7 shows a comparison of AdBlue consumption at idle for a single-engine variant (CAT C175) and a two-engine variant (CAT C13B and C175) as a function of idling time. In the two-aggregate variant, thanks to the reduction in the running time of the C175 main engine, the savings in AdBlue consumption are estimated to range from PLN 8828.35 to PLN 13,242.53 in one year of locomotive operation.

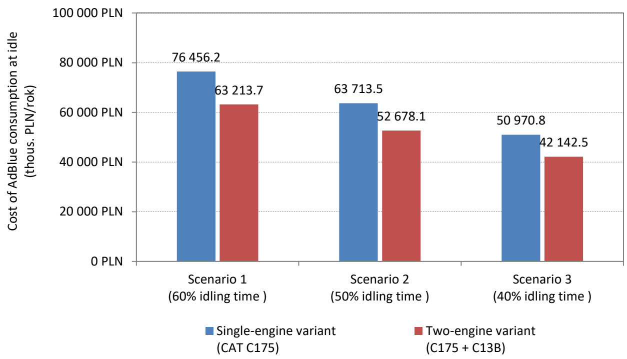

Fig. 7. Comparison of the annual cost of AdBlue consumption at idle for the single-engine variant and the two-engine variant depending on the operating scenario

5.5. Environmental cost comparison

The EU ETS (Emissions Trading System) is part of the Fit for 55 legislative package. According to the amendment to the ETS reform adopted by the European Parliament in April 2023, the obligation to purchase emission allowances will be extended to the automobile, air, and water transport sectors, starting in 2027 (it was initially scheduled for 2024). The EU ETS reform was supported by the Community of European Railway and Infrastructure Companies

(CER). In the next phase of regulatory changes, it is expected that diesel traction in rail transportation will also be subject to these additional costs.

Given these requirements, it is necessary to compare the environmental impact, particularly the carbon dioxide (CO_2) and other pollutants emitted by the single- and two-engine variants.

Table 10 shows the unit emission values for the single- and two-engine variants of the locomotive under idling conditions, while Tables 11 and 12 show the annualized values in kg/year for the three operating scenarios subject to analysis.

Table 10. Specific emission values under locomotive idling conditions

No.	Specification	Single-engine variant (C175 engine)	Two-engine variant (C175 engine + C13B engine)
1	NO_x [g/h]	935	26
2	CO [g/h]	1206	34
3	HC [g/h]	27	5
4	CO_2 [kg/h]	318	208

Table 11. Emission value at idle in the single-engine variant (C175 engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
NO_x [kg/year]	3590.4	2992.0	2393.6
CO [kg/year]	4631.0	3859.2	3087.4
HC [kg/year]	103.7	86.4	69.1
CO_2 [kg/year]	1221.1	1017.6	814.1

Table 12. Idle emission value of the two-aggregate variant (C175 engine + C13B engine)

Specification	Scenario 1	Scenario 2	Scenario 3
Idling time [hr]	60% – 3840	50% – 3200	40% – 2560
NO_x [kg/year]	99.8	83.2	66.6
CO [kg/year]	130.6	108.8	87.0
HC [kg/year]	19.2	16.0	12.8
CO_2 [kg/year]	798.7	665.6	532.5

The unit costs of carbon dioxide and other pollutants were adopted by Annex No. 2 to Prime Minister's Order No. 559 of May 10, 2011, on mandatory bid evaluation criteria other than price for certain types of public procurement (Journal of Laws 11.96.559 of 10.5.2011) – Table 13.

Table 13. Unit costs of carbon dioxide and pollution emissions [23]

Carbon dioxide CO_2	Nitric oxide NO_x	Hydrocarbons HC	Particulate matter PM
0.115–0.154 [PLN/kg]	0.0169 [PLN/g]	0.00384 [PLN/g]	0.334 [PLN/g]

The chart compares the annual cost of CO_2 emissions and other pollutants contained in the exhaust at idle for the single- and two-engine variants. The analysis indicates that the savings in environmental expenses for the two-engine variant are estimated at up to 49.9%, i.e., from PLN 82,909.64 to PLN 124,364.47 depending on the scenario, over the course of one year of locomotive operation.

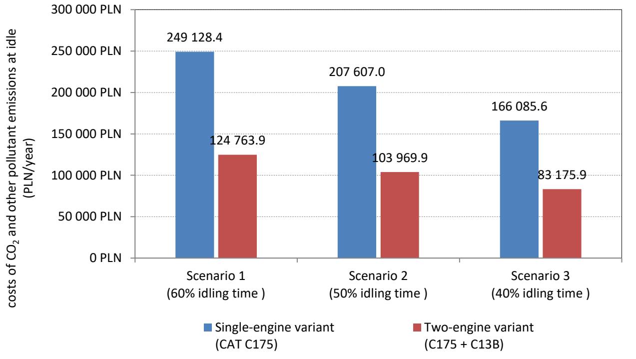

Fig 8. Comparison of the annual costs of CO_2 and other pollutant emissions at idle for the single-engine and twin-engine variants, depending on the operating scenario

5.6. Summary of the effectiveness of the single- and two-engine variants

Table 14 summarizes the efficiency of the single- and two-engine variants in terms of the drive system configuration for three operating scenarios that differ in the share of the locomotive idling time in the total operating time:

1. Scenario 1: 60% idling time
2. Scenario 2: 50% idling time
3. Scenario 3: 40% idling time.

Table 14. Summary of single- and two-engine variant efficiencies for three scenarios

Specification	Two-engine variant [thous. PLN/year]	Single-engine variant [thous. PLN/year]	Savings [thous. PLN/year]
Scenario 1	2180.1	3200.4	1020.3
Scenario 2	1907.2	2790.4	883.2
Scenario 3	1928.7	2380.4	451.7

In all scenarios analyzed, the two-engine variant proves more economical than the single-engine variant. The largest savings were achieved in Scenario 1, where the idle time share was as much as 60%. In this case, the annual operating costs for the two-engine system amounted to PLN 2180.1 thousand, while for the single-engine system it was as much as PLN 3200.4 thousand. This translates to savings of approximately PLN 1020.3 thousand per year. As the idle time share decreases, the difference in costs between the variants decreases. In Scenario 2 (50% idle time), the savings amount to PLN 883.2 thousand, while in Scenario 3 (40% idle time), they are only PLN 451.7 thousand. PLN. This trend indicates that the advantage of the two-engine variant is particularly visible in conditions of frequent idling of the locomotive, while in scenarios with a lower share of this mode, the economic difference gradually decreases.

6. Conclusions

The comparative analysis demonstrated clear advantages of the two-engine drive system for high-power diesel locomotives, especially in idling conditions. The use of a smaller auxiliary engine reduces wear on the main unit, contributing to lower maintenance costs and improved energy efficiency.

In addition to the economic aspects, the dual-engine solution proved to deliver significant environmental benefits. Reduced fuel consumption and lower CO_2 and NO_x emissions make this configuration more compatible with tightening EU regulations and climate policy targets.

Another advantage of the two-engine configuration is increased operational flexibility and system reliability. Adjusting power output to real traction needs allows for better adaptation to varying operational scenarios and reduces the risk of failures.

Although the investment costs of the dual-engine variant are higher, the estimated payback period of 3–5 years makes this solution attractive in the long term. Considering the nominal service life of locomotives, this approach provides strong justification for further development.

Future work should include a broader range of operating scenarios and experimental validation of the simulation results, as well as an assessment of the life-cycle environmental impact of multi-engine locomotives. Comparative studies with hybrid and alternative-fuel solutions could also provide valuable insights into sustainable strategies for non-electrified railway lines.

Similar comparative analyses of locomotive drive systems have been undertaken by other researchers, but the scope has so far been limited, mainly focusing on fuel consumption and emissions. The present study extends this perspective by combining technical, economic, and environmental aspects, highlighting the potential of dual-engine locomotives as a competitive solution for the future.

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