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Analysis of the selection of the auxiliary drive system for a special purpose hybrid rail vehicle

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Strict emission standards mean that the internal combustion engines used in means of transport must meet the standards for the emission of harmful compounds. For this reason, there is an increase in the use of alternative sources of propulsion, including rail transport. The article presents unconventional solutions of drive systems in rail vehicles using hybrid systems and fuel cells. The concept of the realizing project of a special-purpose rail vehicle, which is to be able to be driven from three different sources, was presented. Considerations concerning the selection of the internal combustion propulsion system, which is to be used as an auxiliary in the vehicle, are described. The possibilities of installing the power unit on the vehicle were also presented.

1. Introduction

The rolling stock comes in many forms and is designed for numerous tasks, which are often highly specific and different from those of other vehicles. These differences result in a significant divergence in the operating characteristics and parameters of these vehicles. This significantly complicates the selection of key components and assemblies, which are limited by their specific range of work and parameters. The main aspect that determines a new vehicle design is the drive system and its components. Thus, the criteria for selecting drive units and their parameters depend on the type of work expected to be carried out by the designed vehicle. For example, a passenger rail vehicle will typically be significantly different from a freight or shunting locomotive. Special-purpose vehicles often require all the more specific and unique characteristics and parameters. Depending on the operating conditions, the use of rail vehicles with electric drives may not be possible, mainly due to the limited level of electrification of railway lines in Poland, estimated at over 60% [10]. As a result of these limitations, along with the need to reduce exhaust emissions and the demand for hydrocarbon fuels on the market of rail vehicles, new alternative or mixed solutions are emerging, based on electric supply from electrified lines, with the possibility of driving and operating the vehicle outside the reach of catenary for a limited period of time or without such limitations. Such solutions allow to reduce the need for rail vehicles to operate powered by the combustion engine. This means that it is possible to use the internal combustion engine only when it is necessary or in an emergency. Another solution is to incorporate vehicles with alternative drives into a larger consist in order to reduce its environmental impact. Such an effect can be obtained by using the alternative propulsion actively when the internal combustion engine reaches operating points with low efficiency or high emissivity. Another approach is to use batteries or other energy storage systems that allow the vehicle to temporarily operate on the non-electrified lines. However, this solution does not allow the vehicles to be fully independent from electrified railway lines. All the discussed solutions are intended to replace the

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existing technologies of rail vehicles propulsion, which usually require electric traction or pose a health risk to people in their vicinity through the emission of toxic compounds in the exhaust gases.

The negative impact on the environment and the growing awareness of the problems related to the emission of carbon dioxide and other toxic compounds influencing global warming results in the development of new, more ecological technologies in all branches of transport. The results of this development can mainly be observed in road vehicles, but it is possible to use similar solutions in rail vehicles as well, provided appropriate adaptations are made. As the estimated age of the rolling stock is high, especially in Poland, where it is around 33 years for locomotives [1] changes in the drive system technology of these vehicles will be reflected by a gradual reduction of exhaust emissions. This means that in order to achieve notable reduction in exhaust emissions from rail vehicles, changes to the rolling stock available on the market have to be introduced well in advance. While the environmental performance of the vehicles purchased over the last two decades were characterized by better environmental indicators (in line with the tightened legal requirements for exhaust emissions), they will still have a negative impact on the environment, which will continue until they are withdrawn from service and decommissioned. The necessity to replace the vehicles in use currently with modern rolling stock leads to the development of new, less environmentally harmful solutions for vehicle drive technology, including special-purpose vehicle propulsion systems, which are discussed in this article.

2. Examples of alternative drive systems in modern rail vehicles

2.1. Hybrid drive systems

Hybrid drive systems are more commonly associated with road vehicles. Popularity of the electrification [21] of transport means is increasing due to its ability to limit the negative impact on the natural environment by reducing the operation time share of the internal combustion engine. This trend can also be found, to a lesser extent, in the non-road vehicle sector [14], as well as in rail transport [25].

About 62% of Polish Railway Lines are electrified, and in five voivodeships this share does not exceed 40% [20]. In the case of the EU-27 countries, this average is 56% [11]. As a result it is not possible to use rail vehicles that depend only on the overhead contact line in all sections for power. In this case, it is reasonable to use vehicles with their own propulsion source, such as an internal combustion engine. However, the use of this solution is associated with the inevitable local emission of harmful exhaust compounds. A rail vehicle with a hybrid drive system is a solution that combines the advantages of using the overhead contact line, where available, and the independence of the diesel powered drive system.

Rail vehicles designs with hybrid drive systems have already been developed in Poland. One of them is a passenger railcar designed by Łukasiewicz Research Network – Rail Vehicles Institute “TABOR” and produced by H. Cegielski-FPS. The 227M vehicle is a design consisting of two segments: combustion and electric (Fig. 1 and Fig. 2). Each segment is specially designed for the use of a specific drive system type, i.e. in the combustion segment there are two power generators that enable driving in the combustion mode (Fig. 3) [8], and in the electric segment devices necessary for the collection and processing of electric energy from overhead electric traction. Table 1 shows the 227M vehicle technical parameters.

Table 1. The technical parameters of the 227M vehicle

Parameter	Value
Length of the entire multiple unit	53 100 mm
Total empty vehicle mass	110 t
Total mass of the vehicle at full passenger capacity (4 persons/m^2)	127 t
Number of seats: fixed/foldable	80/3
Number of standing places (4 persons/m^2)	145
Vehicle speed when powered from the overhead catenary	160 km/h
Vehicle speed when powered by on-board power generators	120 km/h
Combustion engines power	2 × 400 kW@1900 rpm
Combustion engines max. torque	2 × 2500 Nm@1200 rpm
Power of electric motors	4 × 300 kW

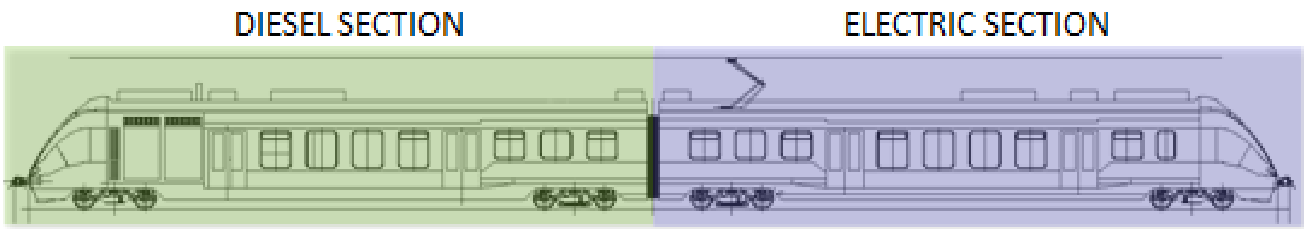

Fig. 1. Type 227M rail vehicle consisting of two segments: diesel and electric [28]

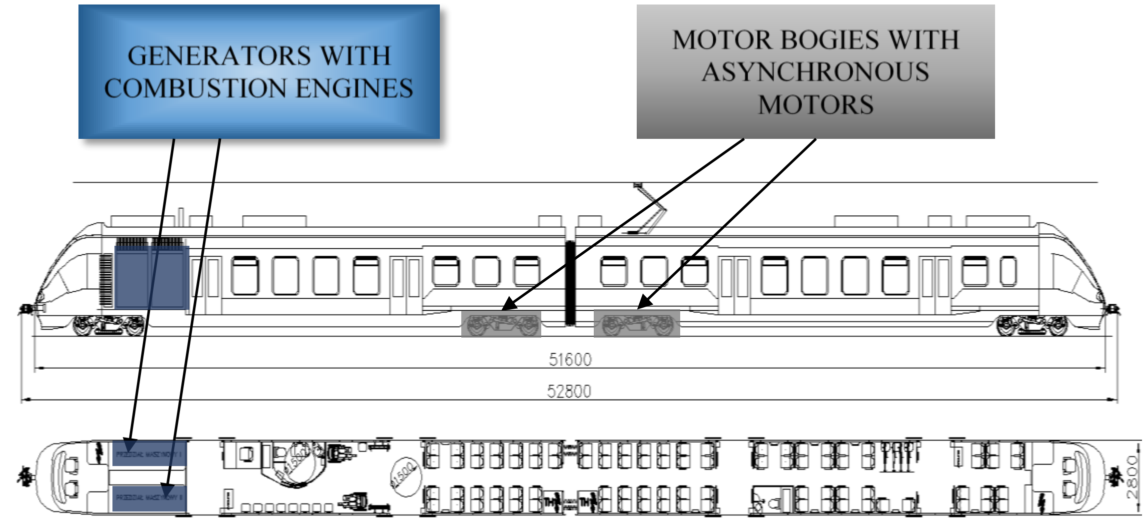

Fig. 2. Location of generating sets and motor bogies [8]

Fig. 3. Built-in powerpack generator in the type 227M rail vehicle [8]

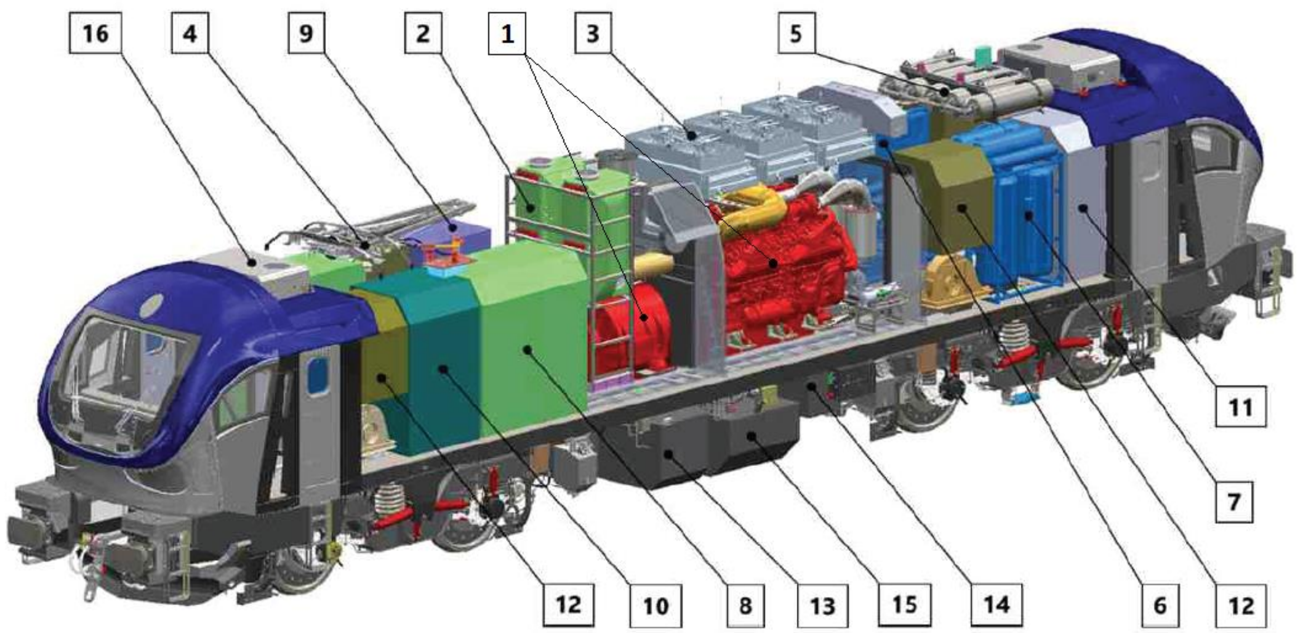

Fig. 4. Layout of equipment on the 111DE locomotive, 1 – power generator, 2 – a set of SCR catalytic systems, 3 – combustion engine cooling unit, 4 – pantograph, 5 – main air tanks, 6 – compressor module, 7 – board module, 8 – power inverters cabinet, 9 – cooling column with braking resistor, 10 – HV cabinet, 11 – ETCS cabinet, 12 – LV cabinet with electric motors ventilator, 13 – line choke, 14 – battery box, 15 – fuel tank, 16 – air conditioning unit [19]

Another example of rail vehicles that can use two power sources for propulsion are the double-drive locomotives type 111DE (Fig. 4) and 111Ed (Fig. 5), designed by Łukasiewicz Research Network – Rail Vehicles Institute "TABOR" , and manufactured by Rail Vehicles PESA Bydgoszcz S.A. [3]. Depending on their type, these vehicles can use two drive systems: one powered from the overhead catenary and one powered by a power generator. This solution makes the four-axle locomotive universal. The vehicle can be used on any section of the railway line, whether it is electrified or not. In addition, such a vehicle is highly versatile as it can perform various transport tasks in freight and passenger traffic as well as shunting work where the lines are not electrified. Vehicles of this type are dedicated especially to Undertakings involved in intermodal transport and dispersed goods transport [19].

Fig. 5. Type 111Ed locomotive [12]

2.2. Fuel cells

Hydrogen is one of the most promising forms of energy storage and production. It is an environmentally friendly solution due to its usage having close to zero emissivity. Contrary to the combustion of hydrocarbon fuels, where the combustion products, in addition to steam and heat of combustion, include such harmful compounds as: CO_2, CO, HC, NO_x as well as particulate matter (PM) [4, 17], the combustion of hydrogen result in the production of water vapor [26, 27] and when the temperature is high enough also the formation of NO_x compounds. Hydrogen can also be used in fuel cells, the so-called Fuel Cell Hydrogen (FCH) [5, 24]. In this case, the products of the chemical reaction are just water vapor, heat and electricity, which is then used to drive electric motors [9]. Ultimately, hydrogen is considered the future application for these types of solutions. According to estimates, replacing trains equipped with CI engines operating on the Gdynia-Hel-Gdynia section with trains powered by hydrogen fuel cells, where the hydrogen is produced from renewable energy sources, could reduce the annual CO_2 emissions from this service by 2505 tons [23].

Fuel cells are already used in rail transport [16, 22]. One of the most recognizable implementations of hydrogen cells in rail vehicles is the Alstom Coradia iLint vehicle (Fig. 6). The train was used commercially for the first time in September 2018. At the same time, these vehicles replaced the combustion vehicles used so far on the 100 km route running through Cuxhaven, Bremerhaven, Bremervörde and Buxtehude in Lower Saxony, Germany [6]. Coradia iLint vehicle data and parameters is shown in Table 2.

Fig. 6. Coradia iLint [6]

Table 2. Main parameters of the Coradia iLint [9]

Parameter	Value
Max travel speed	140 km/h
Range at full tank	1000 km
Service mass of a single segment	49 t
Hydrogen tanks volume	94 kg

In Poland, the project concerning hydrogen drive for rail vehicles was undertaken by the Bydgoszcz manufacturer of rail vehicles PESA [7]. Work is currently underway on a hydrogen-powered shunting locomotive, and more precisely, the modernization and adaptation of the SM42 locomotive to a hydrogen powered drive system. After the works are completed, the locomotive is to receive the designation SM42 6Dn (Fig. 7). Basic vehicle data was presented in Table 3.

Table 3. Operating parameters of the SM42 6Dn hydrogen shunting locomotive [9]

Parameter	Value
Max. speed	90 km/h
Service mass	< 70 t
Fuel cell power	85 kW × 2
Expected fuel consumption	< 0.08 kg/kWh
DC voltage supply	< 800 V
Battery capacity	> 160 kWh
Hydrogen tanks capacity	175 kg
Operating temperature range of the fuel cell	–40°C to +85°C

Fig. 7. The hydrogen locomotive SM42 6Dn and hydrogen fuel cells powering it produced by PESA Bydgoszcz presented at the International Railway Fair TRAKO 2021 [9]

Projects concerning the use of fuel cells in shunting locomotives have also been appearing abroad. An example is the conceptual project of the MaK G1206 diesel shunting locomotive conversion into an FCH locomotive (Fig. 8). The project team calculated the necessary parameters for the vehicle drive and energy storage systems, which included components such as a battery energy storage, a fuel cell system, a cooling system for both batteries and fuel cells, and a hydrogen tank. The paper also presents the calculations of energy demand and data on components for the discussed drive system ensuring that at least three heavy shunting tasks can be performed (Table 4). The weight of the entire new drive system was 9900 kg and its total volume was 16.5 dm^3 [15].

Table 4. Component layout for the most demanding profile combination (3× heavy shunting) [15]

Component	Designation	Quantity	Installation size
Fuel cell	Hydrogenics HD 30	18	540 kW
Fuel cell cooler	AKG W40	18	780 kW
Battery	Akasol 18 AKM 46	10	368 kWh
Battery cooler	Technotrans zeta.line 450	1	45 kW
Hydrogen tank	Luxfer W320H	13	100 kg

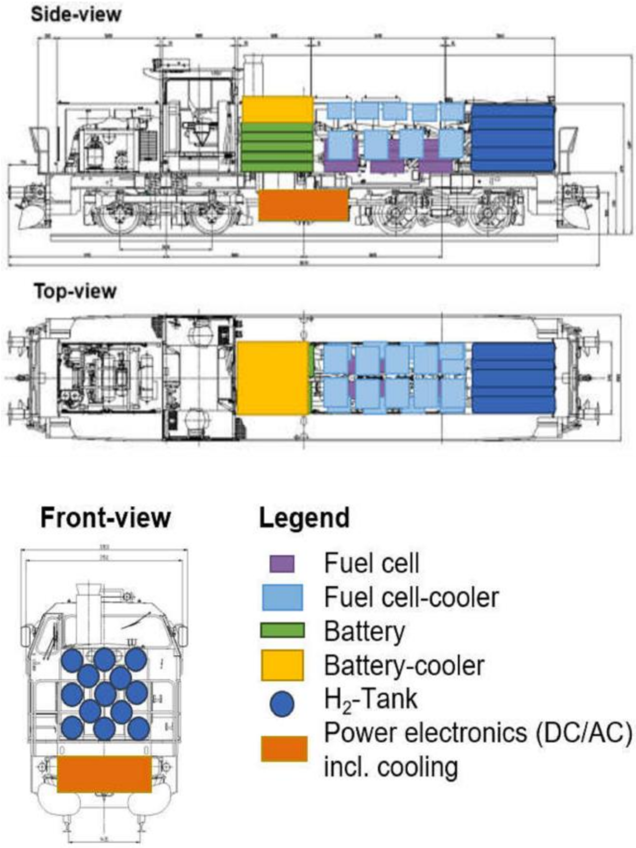

Fig. 8. Arrangement of the components on a MaK G1206 locomotive [15]

3. Special purpose rail vehicle

The development of sustainable transport in Poland plays an major role in the steps taken towards improved environmental protection. Therefore, ZPS LLC (Railway Vehicle Plant), together with Łukasiewicz Research Network – Rail Vehicles Institute "TABOR" (now Łukasiewicz – Poznań Institute of Technology, Center of Rail Vehicles) are implementing a project as a part of the Fast Track competition entitled "An innovative, special railway vehicle with a hybrid drive, equipped with energy storage systems, as vehicle base for the assembly of devices intended for the construction, diagnostics and measurements of railway infrastructure", project no. POIR.01.01.01-00-1601/20 concerning the construction of a new, innovative special railway vehicle with a type 501EH hybrid drive system. The vehicle will be equipped with elements such as a crane with workman basket and basket platform, a workshop compartment and a social compartment (Fig. 9). The most important challenges for an environmentally friendly special purpose vehicle include:

- designing the vehicle's powered bogies adapted to the travel speed of 160 km/h,
- hybrid drive system,

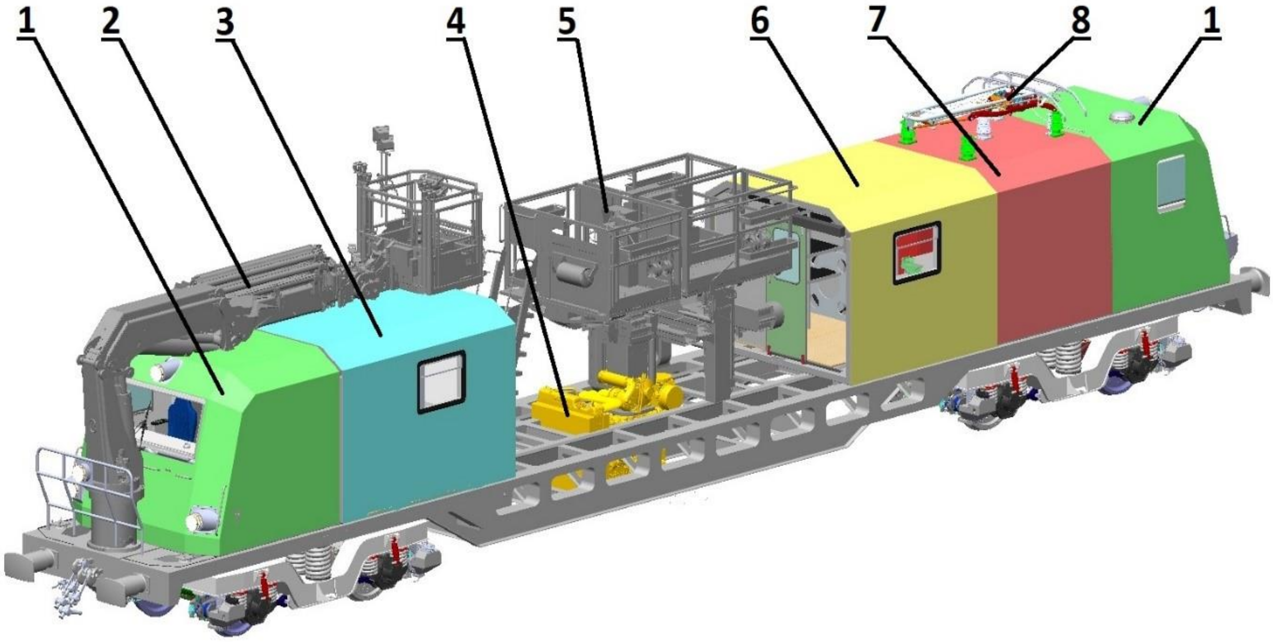

Fig. 9. The initial concept schematic of a 501EH special purpose vehicle; 1 – driver's cabin, 2 – cherry picker basket and arm, 3 – crew rest compartment, 4 – combustion engine, 5 – cherry picker platform, 6 – workshop compartment, 7 – electrical module, 8 – pantograph

- implementation of new, environmentally friendly systems for processing and storage of electricity, such as battery energy storage,
- reduction of harmful exhaust compounds emissions,
- modern and intuitive driver's interface.

One of the more interesting design developments is the new hybrid powertrain. Ultimately, in conventional travel conditions, i.e. driving on electrified sections, the vehicle will draw electric power from the traction network through a pantograph. Upon arrival at the place of work, the vehicle shall be capable of operating using energy from its energy storage devices. The selection of the energy storage system with the required operational parameters will take place at further stages of the project, however, the use of modern battery stacks or supercapacitors would be considered. These solutions would also allow the use of a braking energy recovery system. This would increase the overall energy efficiency of the vehicle in operation. During braking, the generated electricity would go to the energy storage system, and should the system capacity be full, the energy would be sent back to the traction network.

The rolling stock vehicles that serve technical support and maintenance roles are typically powered exclusively by compression-ignition (CI) combustion engines. The use of such a vehicle to carry out stationary works leads to the emission of toxic compounds such as HC, CO, NO_x as well as particulate matter (PM) from the combustion of hydrocarbon fuels in the area where it is located, which in turn increases the health risk of employees working in that area and has a negative impact on the local environment. For this reason, the vehicle described in the article will be equipped with an internal combustion engine, the main task of which will be to power the vehicle in emergency situations, i.e. failure of the primary power supply (electric traction and energy storage). During the failure, the engine will work together with the generator as a power generator.

The selection of an appropriate combustion engine was one of the key stages of the vehicle design process. This article presents only preliminary considerations for the engine selection, based on the engine units used in previous projects. The actual engine units will be selected at a later stage through tendering. The article gives consideration to drive units used in vehicles designed by the ZPS company in the past based on the previously obtained experience in engine selection. Due to the nature of the vehicle's operation, its weight, available space for equipment and the vehicle's demand for power during combustion mode – based on the experience of the rolling stock manufacturer, among other things, which was gained during the implementation of previous projects – two internal combustion engines of an American engine manufacturer Caterpillar were taken into account. More precisely, they were the C9.3B and C13B engines. The design of the two engines is similar, both are four-stroke inline six-cylinder units. The difference results mainly from the displacement volume, and thus the performance (Table 5). The most important differences are the engine nominal power and torque values. The C9.3B engine reaches 340 kW of maximum power and a torque of 2,088 Nm, while the C13B, which is larger by 3.2 dm^3, achieves a power output of 430 kW and a torque of 2,640 Nm.

Table 5. Technical parameters for CAT C9.3B and CAT C13B engines [2]

Parameter	C9.3B	C13B	Unit
Engine configuration	6 In-line, 4-stroke engine	6 In-line, 4-stroke engine	[-]
Bore	115	130	[mm]
Stroke	149	157	[mm]
Displacement	9.3	12.5	[dm^3]
Aspiration	Turbocharged-Aftercooled (TA)	Turbocharged-Aftercooled (TA)	[-]
Engine power	340@2000	430@1800–2100	[kW@rpm]
Peak torque	2088@1400	2640@1400	[Nm@rpm]
Compression ratio	17:1	15.8:1	[-]
Fuel type	Diesel	Diesel	[-]
Ignition type	Compression Ignition	Compression Ignition	[-]
Max operating altitude	2240	2037	[m]
Combustion system	Direct Injection	Direct Injection	[-]
Turbo configuration	Single	Single	[-]
Turbo quantity	1	1	[-]
Exhaust emission standard	Stage V/Tier 4	Stage V/Tier 4	[-]

The difference in the swept volume between the engines also affects their dimensions and mass. The C13B engine is notably bigger and 260 kg heavier than the C9.3B (Table 6). It should be remembered that an internal combustion engine also requires a cooling, lubrication and exhaust aftertreatment systems. The larger the engine, the more efficient and bulky the supporting systems need to be.

Table 6. Dimensions of CAT C9.3B and CAT C13B engines [2]

Parameter	C9.3B	C13B	Unit
Height	1068	1134	[mm]
Length	1125	1274	[mm]
Width	791	994	[mm]
Weight – Net Dry – Basic Operating Engine Without Optional Attachments	865	1125	[kg]

For Non-Road Mobile Machinery (NRMM) vehicles, which also include rail vehicles, the latest emissions standard in Europe is Stage V [13]. The considered engines belong in the non-road engines (NRE) group, which are dedicated to be mounted into NRMM vehicles. In the certification process, these units are required to pass the Non-Road Stationary Cycle (NRSC) and Non-Road Transient Cycle (NRTC) exhaust emissions tests, and the specific emission for the relevant harmful compound must not exceed the legal limit. These engines can provide a maximum power of 340 kW and 430 kW respectively, which places them in the NRE-v/c-6 category. The emission limits for Stage V engines were shown in Table 7.

Meeting the increasingly demanding exhaust emission limits often necessitates the use of exhaust aftertreatment systems (ATS). In order to meet the latest exhaust emission norm for proposed engines – Stage V – it was necessary to use a complex exhaust aftertreatment system consisting of a set of catalytic converters and particulate filters. The following elements were used for both engines:

– an diesel oxidation catalytic reactor (DOC), which helps reduce the exhaust emission of selected toxic compounds through their oxidation. This reactor can oxidize the following exhaust compounds: $HC \rightarrow CO_2 + H_2O$, $CO \rightarrow CO_2$ and $NO \rightarrow NO_2$,
– a diesel particulate filter (DPF), which helps reduce the exhaust emission of particulate matter (PM) by oxidizing the particles,

Table 7. Stage V emission norms for non-road engines (NRE) [13]

Category	Ign.	Net Power	Date	CO	HC	NOx	PM	PN
		kW		g/kWh				1/kWh
NRE-v/c-1	CI	P < 8	2019	8.00	7.50[a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50[a,c]		0.40	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	2019	3.50	0.19[d]	3.50	0.045	-

[a] HC+NOx
[b] 0.60 for hand-startable, air-cooled direct injection engines
[c] A = 1.10 for gas engines
[d] A = 6.00 for gas engines

- selective catalytic reduction (SCR) reactor, which reduces NO_x emissions by injecting 32.5% urea solution into the exhaust gas [18].

In order to effectively use a well designed and developed exhaust aftertreatment system a significant amount of free space is needed in the vehicle for its installation and mounting. Table 8 presents the size dimensions of the whole sets of exhaust aftertreatment systems designed for the CAT C9.3B and C13B engines, in order to allow them to meet the current exhaust emission norms.

Table 8. Exhaust aftertreatment systems for CAT C9.3B and CAT C13B engines [2]

Parameter	C9.3B	C13B	Unit
Aftertreatment systems in a set	DOC + DPF + SCR	DOC + DPF + SCR	[-]
Height	432	460	[mm]
Length	925	896	[mm]
Width	694	807	[mm]
Mass	96	100	[kg]

The engine unit, along with the supporting systems mentioned above, requires adequate space on the vehicle for its placement. Therefore, making the right choice when selecting the engine unit to use for the vehicle is a key part of the vehicle design phase, especially when noting the extra space needed on the rail vehicle to install other systems needed by the engine assembly. On the other hand, the engine should have enough power to enable smooth operation along with having some power reserve. Figure 10 is a comparison of the CAT C9.3B and C13B engines, and Fig. 11 shows their dimensions including all the attached systems.

A special-purpose vehicle is ultimately to be equipped with devices intended for repair and maintenance operations. For this reason, the space that can be used for compartments on the vehicle's undercarriage frame is very limited. This also applies for the selection of a combustion engine and all its support systems as well as a generator. One of the solutions for placing the generator set, which has already been used in other vehicle designs, was the use of space in the structure of the undercarriage. These types of structures make it possible to utilize the unused space, to lower the center of gravity of the vehicle, and to allow for more ergonomic placement of parts, devices and compartments on the undercarriage. Such a solution also significantly increases the available space for the placement and mounting of the main engine and generator systems, i.e. the systems related to electric traction and energy storage, including electrical cabinets, e.g. a high-voltage cabinet, where it was more accessible. It should also be noted that the described vehicle will only use the internal combustion engine in emergencies, by which it is meant that its use will be occasional. An example of the aforementioned design solution on another vehicle was provided in Fig. 12.

4. Conclusions

The presented theoretical analysis of the engine unit selection in a special-purpose vehicle with a 501EH hybrid drive system was determined on the basis of multiple parameters. Among the most significant of those were the engine operating parameters, i.e. its characteristics, power and torque, as well as the

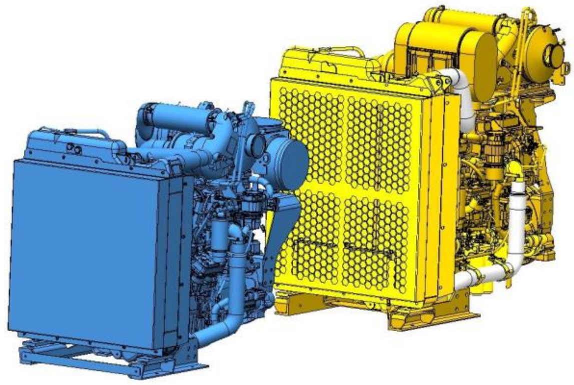

Fig. 10. A list of internal combustion engines proposed for installation on the 501EH vehicle. Blue color CAT C9.3B engine, yellow color CAT C13B

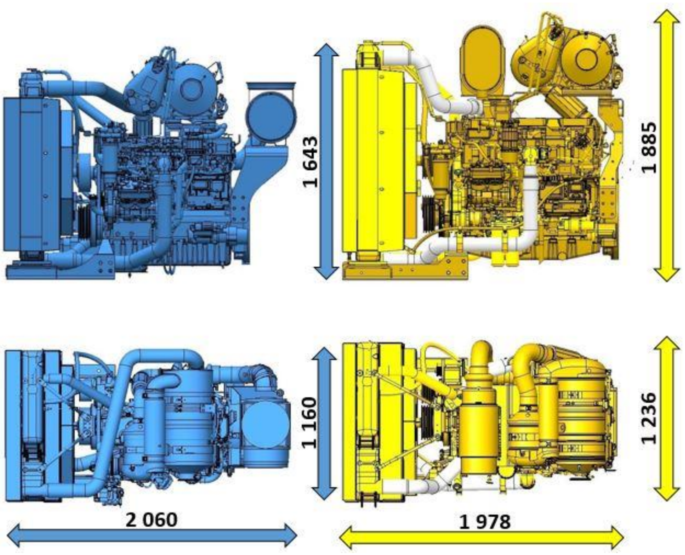

Fig. 11. List of internal combustion engines proposed for installation on the 501EH vehicle with dimensions provided. Top image shows the side view, bottom image shows the top view. Blue color CAT C9.3B engine, yellow color CAT C13B

Fig. 12. An example of a CAT engine mounted in the free undercarriage space of a different type special purpose rail vehicle

parameters and operating conditions of the vehicle itself based on its expected operations, including vehicle ergonomics, reliability and stability. Due to the space limitations associated with using a larger, more powerful engine, which required larger and more efficient supporting systems and components, including the exhaust aftertreatment system, it was necessary to use modern design and production methods, as well as modern materials and technologies in the presented analysis.

It should be noted that the internal combustion engine in the discussed vehicle concept was assigned the role of a backup or emergency power supply, which is why its frequent use was not considered. Hence, aspects such as the reliability and efficiency of the engine unit were taken into account to a limited extent. Changes to the hybrid drive design were expected to achieve measurable environmental gains, such as lower exhaust emissions and lower environmental impact. As a result, it was possible to avoid more invasive changes and overcomplicating the drive system, which can further improve the servicing and maintenance of the vehicle. Depending on the customer requirements regarding such vehicles, the solutions used may be subject to change.

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European Funds Smart Growth | Republic of Poland | The National Centre for Research and Development | European Union European Regional Development Fund

Nomenclature

ATS	aftertreatment systems
CO	carbon monoxide
CO_2	carbon dioxide
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
FCH	fuel cell hydrogen
H_2	hydrogen
H_2O	water
HC	hydrocarbons
NO_x	nitrogen oxides
NRE	non-road engine
NRMM	non-road mobile machinery
NRSC	non-road stationary cycle
NRTC	non-road transient cycle
PM	particulate matters
SCR	selective catalytic reduction
TA	turbocharged-aftercooled

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