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Authorial concept for the selection of an internal combustion engine for the diesel-electric generator set of a two-unit rail vehicle

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Abstract. An alternative to the diesel-powered vehicles in use today is the light rail vehicle with a dual power train (i.e. with both diesel and electric traction), which can be operated on both electrified and non-electrified lines. The article presents assumptions for the selection of the power unit, taking into account current emission standards, for a vehicle which design solutions are innovative in relation to the rolling stock currently in service. The vehicle takes into account the possibility of driving in electric and diesel traction, the use of an electric transmission (engine + traction transmission), the use of two generators (combustion engine + traction generator), which will increase the reliability of the light rail vehicle and its readiness for operation. By using the electrodynamic brake on the vehicle in electric and diesel traction, energy savings will be achieved, also thanks to recuperation during braking when operating in electric traction, there will be a reduction in fuel consumption in diesel traction through the use of an engine load algorithm depending on the current traction power demand.

1 Introduction

Poland's first fully electrified railway, built from scratch under the name Electric Commuter Railway, was launched on 11.12.1927 as the first standard-gauge electric railway. It connected the town of Grodzisk (since 1928 Grodzisk Mazowiecki) with Warsaw. It was not until 15.12.1936 that the PKP officially opened fully electrified railway lines from Warsaw to Otwock and from Warsaw to Pruszków. The highest rate of electrification of railway networks was in the second half of the 1980s, however, coming to a complete stoppage in 1990. Based on 2022 data, the total length of railway lines in Poland is around 19,000 km, of which around 11,900 km are electrified lines. They account for almost 62% of the total length and this rate is higher than in France, Germany or Spain [4]. Single-track lines account for about 10,500 km and are about 54% of the total length (Figure 1).

The operation of passenger services must meet technical requirements to ensure safe transport. This group is the most numerous of all railway vehicles. It is represented by locomotives, multiple units and passenger coaches. Passenger rolling stock can be subdivided according to the source of propulsion, i.e. into traction vehicles with their own traction system and unpowered rail vehicles which do not have one and are only integrated into the train.

Traction vehicles can be divided according to the type of power system into three groups: autonomous power system, non-autonomous power system and multi-system. Passenger carriages can be subdivided by seating and reclining facilities [6].

Fig. 1. Rail network in Poland

In the last decade, 506 EMUs have been manufactured and are on the equipment of Polish passenger carriers. In the case of Electric Multiple Units (EMUs), the leading manufacturers of this type of traction vehicle were the Bydgoszcz-based Pesa, the New Sącz-based Newag, Stadler and Alstom. Over the period 2010-2019, 88 units were commissioned for production. The multiple units manufactured on behalf of Polish carriers in the last 10 years account for 36% of the total number in use in

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Poland. These figures testify to the high popularity of multiple units in the country [4]. The vast majority of EMUs in Poland (65%) can run at speeds of up to 130 km/h. This is mainly due to the age of the rolling stock and the unsuitability at design level for higher speeds. In 2019, 400 EMUs could run at speeds of up to 160 km/h on the Polish rail network. All units were manufactured in the last decade. There are also 20 units on the domestic market designed to run at speeds higher than 160 km/h. The ED250 (Pendolino) trains produced by Alstom are also the fastest vehicles in Poland. Diesel Multiple Units (DMUs) are mainly used on local lines [1, 6]. The specific nature of this type of transport requires frequent stops, due to the more numerous railway stations. For this reason, high speeds are not required on this type of route. All 196 DMUs in Poland develop speeds of less than 130 km/h.

One way to accomplish the diesel-electric relationship is through internal combustion-powered vehicles (Figure 2). The primary modern energy source for powering vehicles is petroleum-based fuels. These fuels must be replaced by others in the future [2, 6], and it would be expedient to reduce their consumption. Their harmfulness and limited resources make it necessary to search for alternative fuels [2, 7].

However, as well as allowing the transport task to be completed, this solution has key drawbacks:

- internal combustion vehicles have up to twice the acceleration performance and reach lower top speeds, so they are unable to exploit the traction possibilities offered by a railway line with electric traction;
- the majority of railway lines, including railway stations in large cities, are electrified, while outside the cities there are lines for diesel vehicles only. (e.g. Poznań-Wągrowiec); this results in a diesel vehicle entering the city and the railway station where its engine is often running even at a standstill (e.g. to heat or cool the passenger area) - this is environmentally unfavourable.

Fig. 2. Diesel bus of the SA109 series - electric traction (Rzeszów) [60]**.**

Single-track lines, which account for more than half the length of the national railway lines, are a separate problem. If a vehicle breaks down on such a section of the route, it is completely blocked and it is not possible to organise a diversion on the other track. What is left is to wait for another railway vehicle that is capable of towing the defective train to the nearest point where it is possible for passengers to leave safely and for a functioning vehicle to be substituted. At present there is no possibility of reducing the inconvenience of such a situation. The only chance is to reduce vehicle breakdowns and to look for solutions that have so far been unavailable to transport operators, if only for lack of rolling stock with characteristics unique to the one in use to date.

A light rail vehicle with a dual power unit (i.e. both electric and diesel) that can be operated on both electrified and non-electrified lines can provide an alternative to the diesel vehicles currently in use (Figure 3).

Fig. 3. Diesel bus of the SA132 series on the single-track Poznań-Piła route [1, 3]**.**

The benefits of introducing a light electric rail vehicle into service are as follows [2, 3, 7]:

- enabling carriers to launch completely new services on electrified and non-electrified sections with a single vehicle that makes maximum use of the section's traction capacity,
- a reduction in journey times on selected routes due to the possibility of travelling at higher speeds on electrified sections,
- the possibility of launching completely new connections, thanks to their ability to run on routes in poor condition, yet closed to traditional trainsets primarily because of their weight,
- Thanks to the use of two generators, the level of reliability of the rail vehicle and its readiness for operation will be increased, which is particularly important on single-track lines,
- reducing emissions in cities and railway stations with electric traction, by limiting the use of combustion vehicles in these areas.

The introduction of this type of diesel-electric vehicle would allow classic diesel rail vehicles to be redeployed on other lines, providing an opportunity, among other things, to increase the number of feeder services on trunk routes. The arrival of this new type of rolling stock would also make it possible to run trains on new direct routes that do not currently exist, which are currently impossible to operate due to the limited number of diesel rolling stock.

2 Evaluation of existing rail vehicle design solutions

In rail vehicles, a very important component is the driveline, i.e. the set of devices used to transfer the torque generated by the drive unit [3, 4] to the vehicle's drive axles.

Depending on the type of propulsion, a distinction is made between rail vehicles with:

- internal combustion engine and hydraulic (hydromechanical) or electric transmission,
- electric drive and electric transmission,
- hybrid drive, i.e. combining the characteristics of electric propulsion (operation on electrified lines) and diesel-electric propulsion (operation on non-electrified lines) [4, 5].

Up to now, the most commonly used propulsion system in light rail vehicles (Figure 4) is the under-floor system, consisting of an internal combustion engine in a boxer cylinder arrangement (1), a hydraulic (hydromechanical) main transmission (2), articulated shafts (3) and axle gears (with or without a reversing device depending on the type of main transmission used) (4). However, this positioning of the drive does not limit the space inside the vehicle, allowing greater accessibility for passengers.

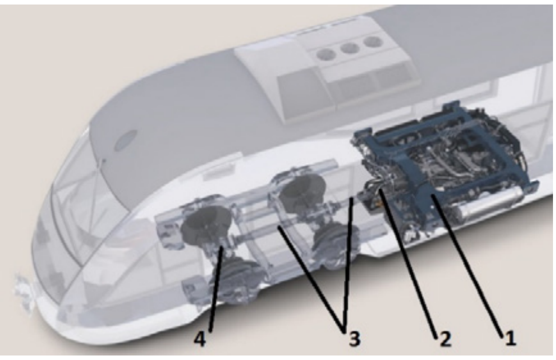

Fig. 4. Underfloor diesel-hydromechanical drive [6].

The location of the drive train under the vehicle floor has its disadvantages [4]:

- difficult access for maintenance and repair work,
- reducing the low floor area of the vehicle,
- the possibility of transferring the drive to one drive bogie only,
- it is not possible to increase the number of sections while at the same time increasing the number of drive bogies, which is necessary to achieve high starting performance,
- only engines with a boxer cylinder arrangement can be used.

Diesel-electric propulsion has been used for many years, particularly in diesel locomotives. This propulsion system will be the basic system in light rail vehicles with higher power output and designed for higher speeds, due to its advantages.

In simple terms, it consists of an internal combustion engine with a flange-mounted traction generator that converts mechanical energy into electrical energy and, via an inverter, powers the asynchronous traction motors on the bogie. These convert electrical energy back into mechanical energy and drive the vehicle's drive axles via traction gears. This solution is used on the Stadler VT646 series vehicle (Figure 5). The short section, based on the drive bogie, functions as an engine compartment with a central passageway for passengers. In a combustion vehicle, it houses, among other things, the internal combustion engine (Fig. 6), while in an electric vehicle, a pantograph is mounted on it and the power electronics are installed inside. The number of sections depends on the length of the vehicle and its traction power requirements.

Fig. 5. Diesel multiple-unit train of series VT 646 (GTW 2/6) of German Railways (DB).

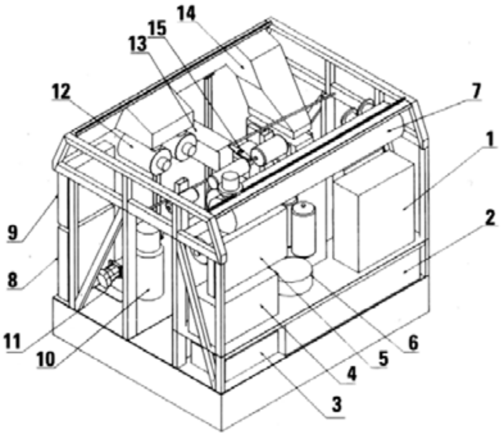

Fig. 6. Arrangement of equipment in the machinery compartment of the GTW2/6 and GTW4/8 vehicle:
1 – inverter, 2 – fuel tank, 3 – batteries, 4 – air preparation unit,
5 – brake panel, 6 – traction motor excitation system,
7 – exhaust silencer, 8 – water cooler, 9 – charge air cooler,
10 – heater, 11 – hydrostatic pump, 12 – air filter, 13 – cooling water expansion tank, 14–- air intakes, 15 – combustion engine

The location of the propulsion system inside the vehicle has features that are free from the disadvantages of the underfloor solution:

- easy access for maintenance and repair,
- does not affect the size of the low floor area in the vehicle,
- the possibility of transferring the drive to any number of drive bogies,
- the possibility of increasing the number of sections while increasing the number of drive bogies, which is necessary to achieve high starting performance,
- the possibility of using internal combustion engines also in inline and V-cylinder arrangements.

However, such an arrangement has one key disadvantage, namely that it limits the space in the vehicle for passengers and is therefore a major challenge for designers [6, 7] due to the minimisation of the size of the compartment required to house the internal combustion engine and the other necessary components of the overall powertrain.

During the development of the vehicle concept, discussions with potential internal combustion engine suppliers revealed that no engines meeting Stage V emission standards were currently available. As the first vehicle was planned to be homologated in 2021, this requirement was imperative. Engine manufacturers declared this possibility, but in the first instance for engines in the government cylinder layout. The reason for this was their greater economic potential than those in the boxer layout. This therefore ruled out the use of a subfloor drive system in a vehicle.

3 Original concept of a diesel-electric two-unit rail vehicle

The basic design considerations for a diesel-electric rail vehicle include (Figure 7):

- the possibility of running in electric and diesel traction,
- thanks to the use of an electric gearbox, the electrodynamic brake is available in both electric and diesel traction (using brake resistors), which will reduce wear and tear on the friction elements of the air brake,
- saving energy through energy recuperation during braking (in electric traction),
- the use of two generators (combustion engine + traction generator) inside the vehicle, which will increase the level of reliability of the rail vehicle and its readiness for operation,
- the use of a drive and rolling carriage in each section, so that the number of drive axles is always 50% and it is possible to exploit the drive and electrodynamic brake capabilities regardless of the number of sections.

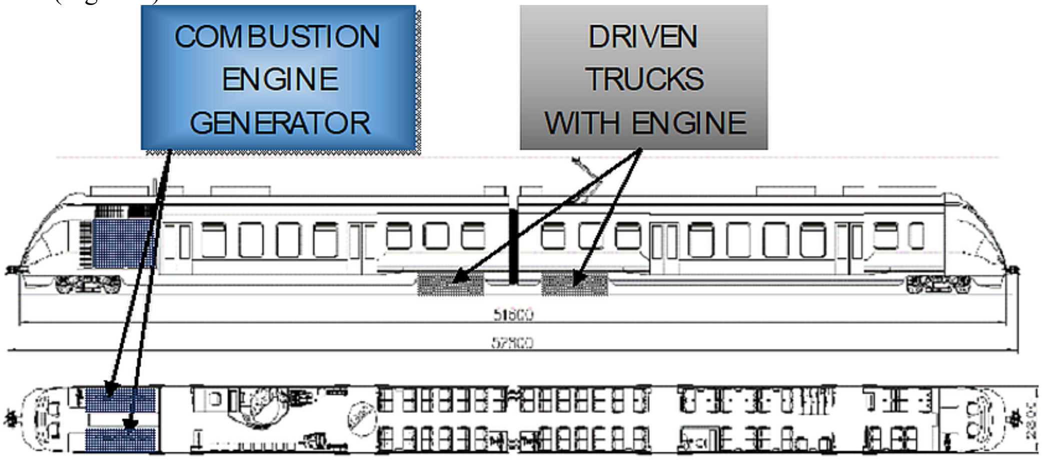

Fig. 7. Concept of the diesel-electric propulsion system of a two-unit rail vehicle.

Due to the considerable length of the engine compartments, where the diesel-powered generators will be built in, together with the alternator and equipment, the vehicle base (distance between bogie axles) has been set at 19,000 mm to provide space for passengers. Unfortunately, this affects the width of the section, which can be a maximum of 2,800 mm due to gauge requirements. The fact that half of the bogies are powered makes it possible to reach a maximum speed of 160 km/h regardless of the number of sections.

The basic technical parameters of the twin-propulsion vehicle can be found in Table 1.

4 Selection of the combustion engine for the diesel-electric generator set of a two-unit rail vehicle

From the point of view of the technical parameters of the vehicle [2, 7], its traction capabilities, maximum speed and expected acceleration, the most important factor is the choice of combustion engine. In the initial design phase, the following requirements were developed, shown in Table 2.

Table 1. Technical characteristics of a two-unit rail vehicle

No.	Parameter	2-unit
1	Overall length of vehicle with bumpers	52 800 mm
2	Section width	2800 mm
3	Unit base	19 000 mm
4	Space for bicycles	4
5	Service compartment	1
6	Space for a ticket machine	2
7	Number of permanent seats	76
8	Number of reclining seats	13
9	Number of standing places (4 persons/m^2)	134
10	Number of wheelchair spaces	2
11	Maximum vehicle speed in electric traction	160 km/h
12	Maximum vehicle speed in diesel traction	120 km/h

The main internal combustion engine selection criteria assumed for this vehicle are as follows:

- meeting emissions standards,
- verification of engine power for expected performance and dynamics,
- space available for the installation of a generator set.

Table 2. Selected requirements for the internal combustion engine

No.	Parameter	Requirement
1.	**Operating and climatic conditions**	
1.1.	Engine housing	Inside the vehicle
1.2.	Vehicle operating speed	160 km/h
1.3.	Parking conditions	Vehicle parking in an open yard
1.4.	Environmental operating conditions of the engine	In a temperature range of -30°C to 40°C outside the vehicle and -30°C to 70°C inside the vehicle in terms of relative humidity - max. 90% at 20°C (annual average 75%)
2.	**Functional and design requirements**	
2.1.	Engine construction type	Diesel, four-stroke in-line
2.2.	Equipment	Internal combustion engine with control unit mounted on its body, air intake system, lubrication system, fuel system without fuel tank, exhaust system (exhaust outlet routed on the roof), enabling Stage V exhaust gas emission standard to be met; cooling system for the internal combustion engine with variable-speed fans (intended installation location on the roof of the vehicle). The engine is required to be suitable for mounting on the outside of the vehicle, with a selected alternator and clutch on its own frame and with selected vibration isolators.
2.3.	Control and diagnostics	The control and diagnostic systems for the electrical equipment in the machinery space must have a self-monitoring function to detect any malfunctions.
2.4.	Engine power	~ 400 kW
2.5.	Rated speed	1700-2000 rpm
2.6.	Rotational idling speed	600-700 rpm
2.7.	Flywheel housing	SAE 1
2.8.	Traction generator drive	Generator construction type: double bearing generator
2.9.	Motor controller voltage	24 V DC
2.10.	Data exchange of the engine controller with the machine compartment controller	CANOpen or CAN J1939 (full data) and in addition hardware signals (activation, status)
2.11.	Starter voltage	24 V DC
2.13.	Maximum engine width	900 mm
2.14.	Design and robustness (attachment of accessories and engine to the vehicle)	acceleration in -x direction: ±3 g acceleration in the direction of the -y axis: ±1 g acceleration in the -z axis direction: ±2 g where: x-axis - longitudinal direction, y-axis - transverse direction, z-axis - vertical direction

The traction characteristics of a vehicle, i.e. the dependence of tractive force as a function of speed F = f(v), are necessary to determine certain traction parameters of a vehicle, e.g. its maximum speed on a specific route, because tractive force and drag force are not constant and depend on speed [2].

DEUTZ TCD 12.0 engines with a power output of 400 kW were adopted for the simulation tests. Based on experience, power analyses of vehicles with similar expected parameters, these powers should be sufficient to provide the expected traction capabilities.

The vehicle's resistance to motion (Table 3) was then determined from 0 to 140 km/h (step $dv = 2$ km/h).

Table 3. Vehicle movement resistance for a two-unit vehicle

Determination of size	Relationships - formulas	Unit	Maximum value
Aerodynamic resistance of the composition	$f_{ae} \times v^2 / 1000 \times 3.6$	kN	8,643
Speed-dependent rolling resistance coefficient	$0{,}53 \times v/g \times 3{,}6$	N/kN	2,101
Total rolling resistance	$f_{RR} + f_{Rts} + f_{Rtv}$	N/kN	4,254
Total composition resistance on a flat track	$R_{ae} + f_{Rt} \times Q / 1000_{\text{poc}}$	kN	12,89

On the basis of the operators' requirements, criteria have been defined to confirm the correct choice of combustion engine power for a 2-unit vehicle (Table 4).

Table 4. Assessment criteria for a two-unit vehicle

Parameter	Value
Maximum speed for 2 × 400 kW	min. 120 km/h (test 120 km/h + 10%)
Maximum speed for 1 × 400 kW	min. 70 km/h (test 70 km/h + 10%)
Average acceleration	min. 0.4 m/s^2 (in the speed range from 0 to 50 km/h on straight track, level, in loaded condition, for 2 × 400 kW)

Simulation studies were then carried out to confirm the validity of this assumption. To this end, the vehicle's traction characteristics, starting distance, instantaneous and average accelerations were determined (Figure 8). In the tests, the vehicle's own needs were taken into account. The minimum is 75 kW, the maximum 193 kW and two intermediate values 112 kW and 150 kW. The result of the simulation studies is the traction characteristics of the 2-unit vehicle, which was divided into 3 areas. In area A (Figure 9) of the traction characteristic curves, the curves of resistance to motion and tractive forces intersect. The intersection points indicate the maximum speed that the vehicle will reach with the assumed parameters. Area B (Fig. 9) of the traction characteristic curve shows the curves of average acceleration. In the point of intersection of these curves with the line indicating a speed of 50 km/h, the average acceleration in the range of 0-50 km/h was read. Area C (Fig. 10) of the traction characteristic curves shows the curves of the start-up paths. At the point of intersection of these curves with the line indicating a speed of 120 km/h, the starting distance in the speed range 0-120 km/h was read.

The resulting traction parameters of the two-unit vehicle are shown in Table 5.

Comparing the assumed criteria (Table 5) with the results of the simulation analysis (Table 4), it was found that the **criteria were met** for a capacity of 800 kW at the maximum assumed own needs:

- maximum speed $v_{max} \geq 120$ km/h (test 120 km/h +10%),
- average acceleration between 0-50 km/h, $a_{śred} \geq 0.4$ m/s^2.

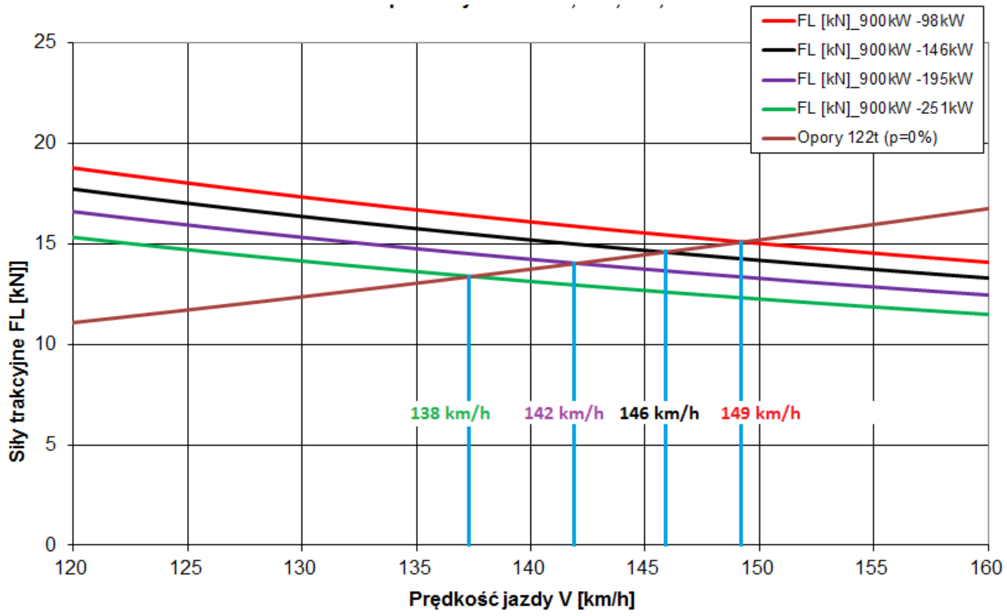

Fig. 8. Area A of traction characteristics of a two-unit vehicle with two 400 kW internal combustion engines; **FL** - traction force, **Opory** - resistance to motion

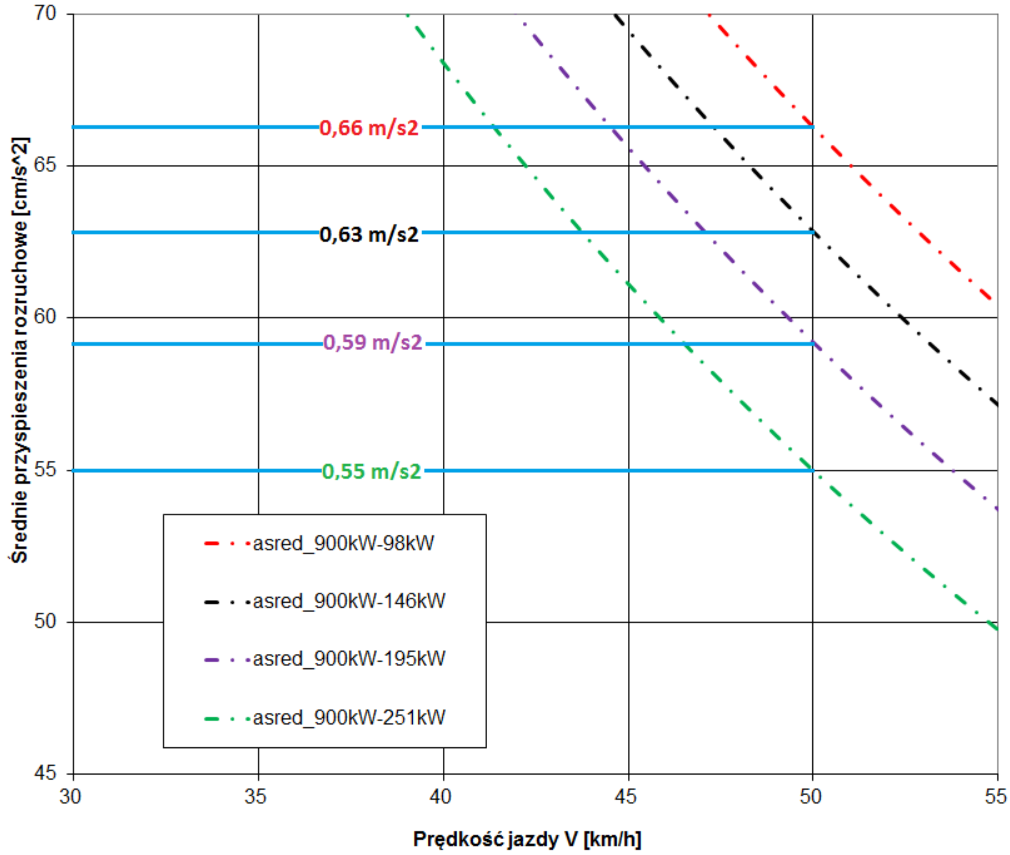

Fig. 9. Area B of the traction characteristics of a 2-unit vehicle with two 400 kW internal combustion engines; **asred** - mean acceleration

Table 5. Values of speed, acceleration and starting distance read from traction characteristics for a two-unit vehicle.

Engine power - Own needs	800 kW–75 kW	800 kW–112 kW	800 kW–150 kW	800 kW–193 kW
Maximum speed [km/h]	149	146	142	138
Average acceleration [m/s^2] between 0-50 km/h (in loaded condition)	0,66	0,63	0,59	0,55
Starting distance [m] to vmax = 120 km/h	3721	4116	4629	5408

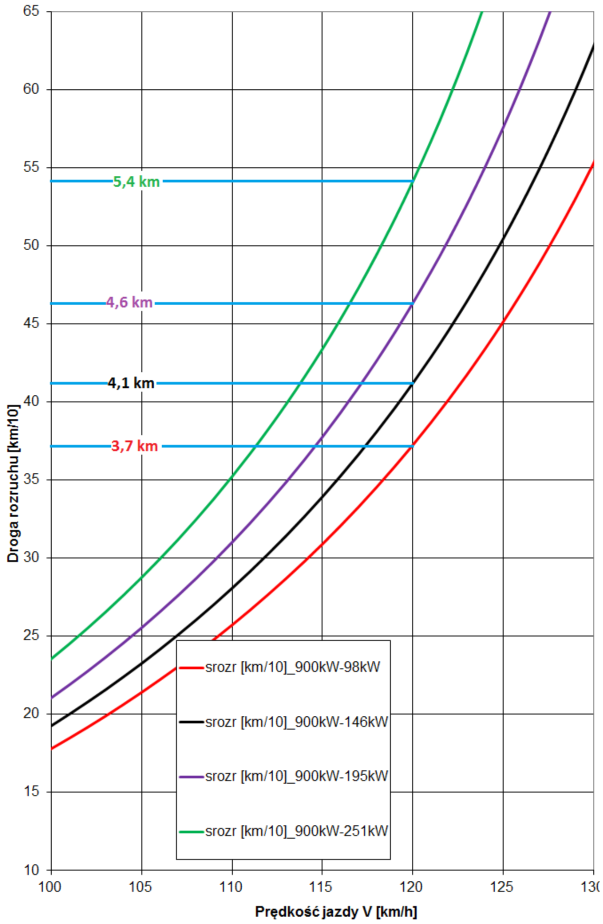

Fig. 10. Area C of the traction characteristics of a two-unit vehicle with two 400 kW internal combustion engines; **srozr** - starting distance

The results of simulation studies indicate that for a two-unit vehicle, 2 400 kW engines are sufficient to achieve a top speed of 120 km/h and average acceleration in the 0-50 km/h range of more than 0.4 m/s^2. They also allow an emergency descent with one functioning engine at a speed of 70 km/h when the vehicle is completely full and maximum own needs.

5 Summary

An original concept for an innovative light rail vehicle with a selected diesel-electric drive system was developed, and innovative systems for propulsion system solutions were proposed. The success of the entire process depended on the adopted scheme of action, guaranteeing the creation of a technically correct, feasible vehicle that meets the functional assumptions and allows safe and economically justified operation of the vehicle. The adopted method, which can be applied to other similar designs of light rail vehicles with hybrid propulsion systems, should consist of several stages:

- reviewing existing propulsion solutions for rail vehicles currently in service,
- determining the basic parameters of the vehicle,
- to identify the critical components of the vehicle, such as the internal combustion engine driving the traction generator, which together constitute the power unit,
- develop criteria for its correct selection and then carry out analyses to confirm that they are met,
- to carry out simulation tests relating to the strength and running gear of structural solutions which are critical from the point of view of railway vehicle construction and will confirm their correctness.

As a result of this work, a vehicle concept was developed and confirmed by simulation studies, which is equipped with generators powered by Stage V emission-compliant internal combustion engines and 2 internal combustion engines with a total power output of 800 kW for a two-unit vehicle, ensuring a maximum speed of 120 km/h and an average acceleration of 0.57 m/s^2 (in the speed range from 0 to 50 km/h on a straight, level track, in loaded condition).

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